Physics motivation for future hh-eh colliders

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CERN

The big questions

We know there are fundamental questions that the SM cannot answer

- What is the origin of Dark Matter / Energy ?
- What is the origin of matter/anti-matter asymmetry ?
- What is the origin on neutrino masses ?
- What is the origin of the Electro-weak symmetry breaking ?
- What is the solution to hierarchy problem ?

There is new physics out there (beyond the Standard Model)

The big questions

Why no new physics at the LHC?

- Two possibilities:
    - New Physics is **within the LHC reach**
        - but it is elusive (and we might see it at HL-LHC)
    - New Physics is **beyond the mass reach** of the LHC
- If the LHC sees nothing**:**
    - roadmap for HEP not as clearly defined as in pre-LHC era
        - no clear no-lose theorem (as with the Higgs)
- Roadmap will consist in exploring new territories:
    - Energy/Intensity frontier exploration

The big questions

- Caveat: no single experiment can:
  - explore all directions at once
  - guarantee discovery

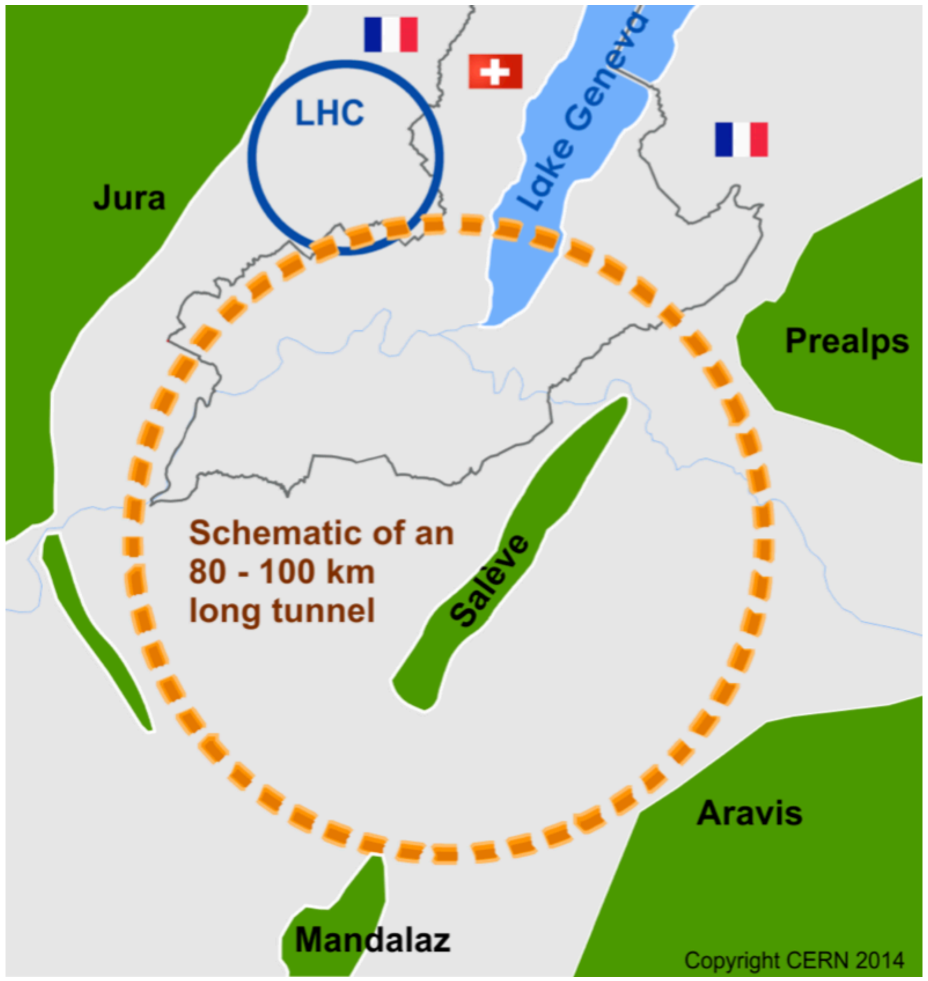
- Goal: design projects that can deliver:
  - precision
  - sensitivity to (as many as possible scenarios of) new physics
  - yes/no answers to concrete scenarios

- HL-LHC will collect data until 2039-2042

- big physics projects take ~20 yrs time to plan and build:

  - now is the right time top start defining the future of HEP

Future machines



Within CERN as host lab, several accelerator facilities have been studied:

- ee-collider (FCC-ee):
  - as a (potential) first step
- pp-collider (FCC-hh)
  - defines infrastructure requirements
  - 16 T → 100 TeV in 100 km tunnel
- HE-LHC :
  - 27 TeV (16T magnets in LHC tunnel)
- Low Energy FCC
  - 37 TeV (6T magnets in FCC tunnel)
- ep collider (LHeC/FCC-eh)
  - 50 GeV - 7TeV / 60 GeV - 50TeV
    - 1 TeV/ 3 TeV E_{CM}

FCC CDR

LHeC

Reach at high energies

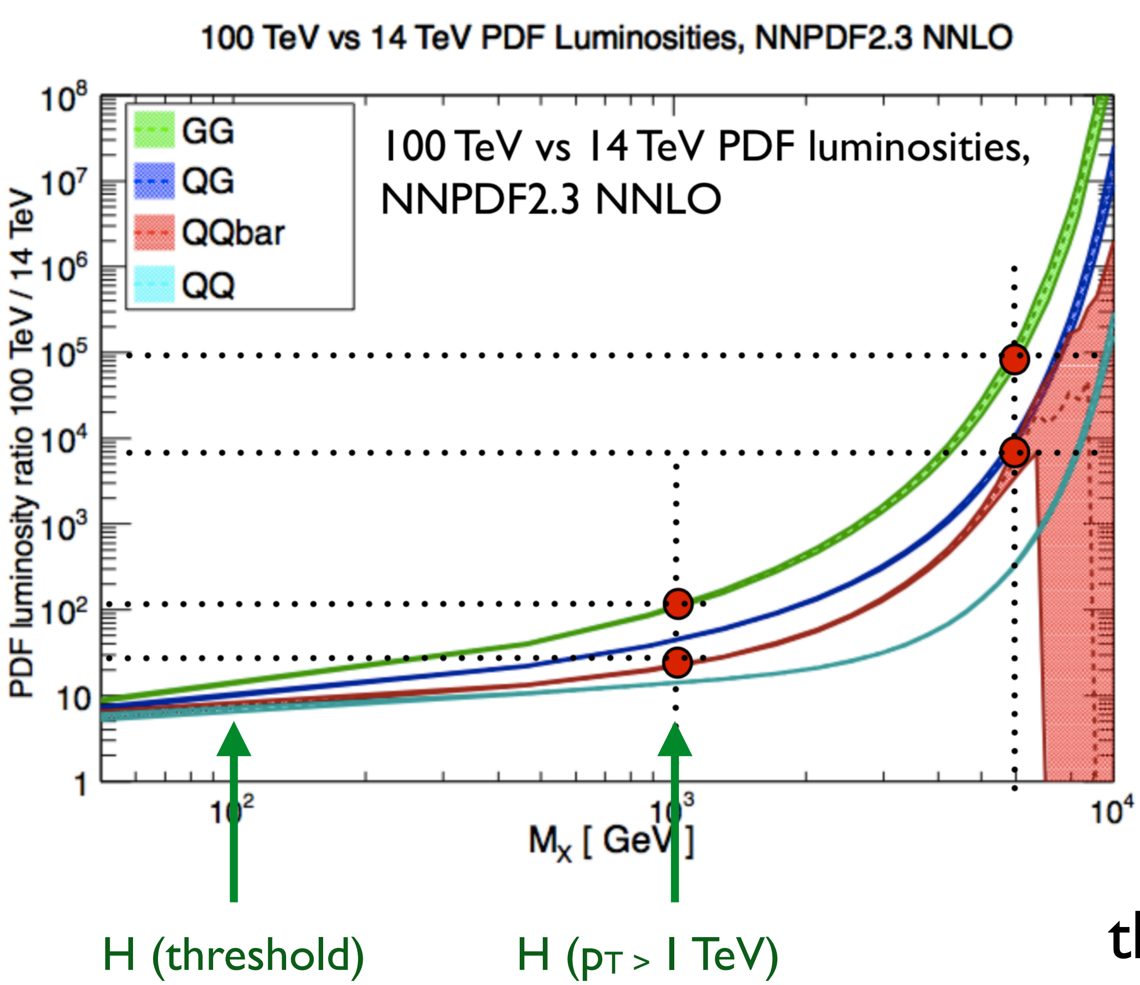
How does the rate of a **given process** (e.g. single Higgs production) scale from 14 TeV to 100 TeV

$\sigma \sim L_{parton}(\tau) \cdot \sigma_{partonic}$

$1/\tau^{a}$ $\quad$ $1/M^2$

$\tau = x_1 x_2 = M^2/s$ $\quad$ assumes mostly produce at threshold

$$\frac{\text{cross-section}\ (\sqrt{s2}, M)}{\text{cross-section}\ (\sqrt{s1}, M)} \approx L_1(M) / L_2(M) \approx (s_2 / s_1)^{a(M)}$$



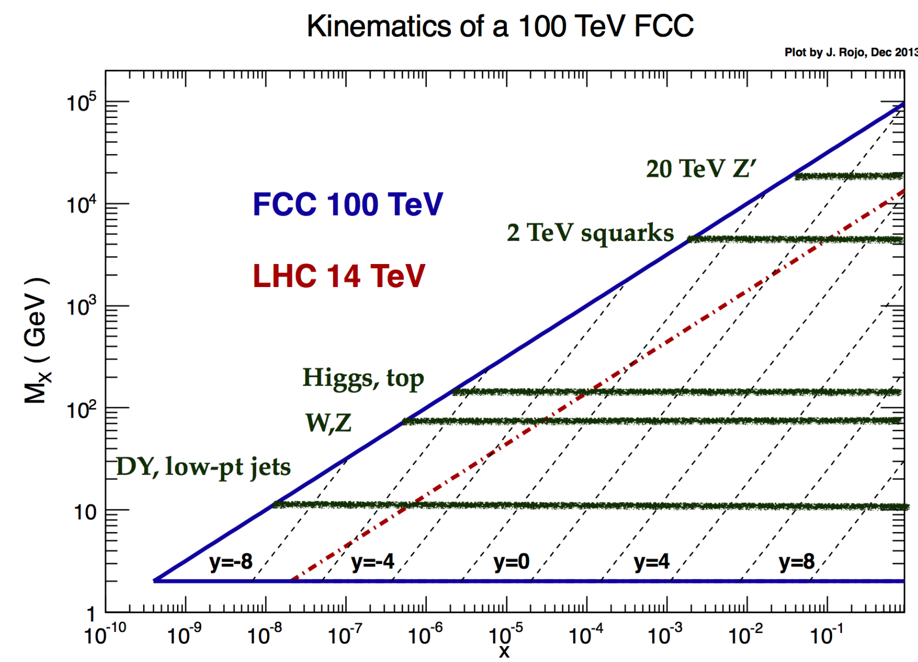
	σ(27)/σ(14)	σ(100)/σ(14)
ggH	3	15
HH	4	40
ttH	5	55
H (p_T > 1 TeV)	7	400

Very large rate increase by increasing center of mass energy

NB: this improvement only comes from the cross-section (neglects integrated luminosity)

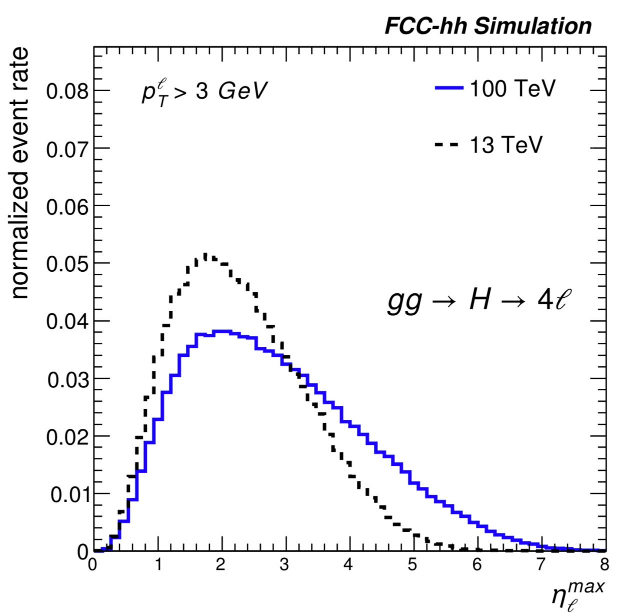
SM physics @threshold

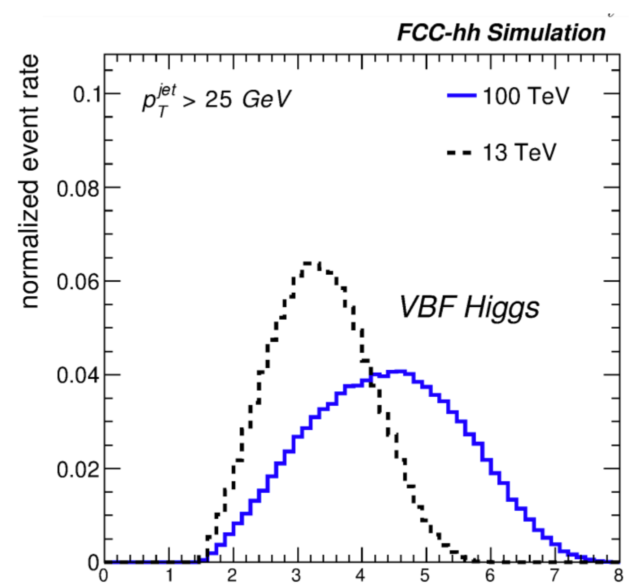
$x_{min} \sim M^2 / s$

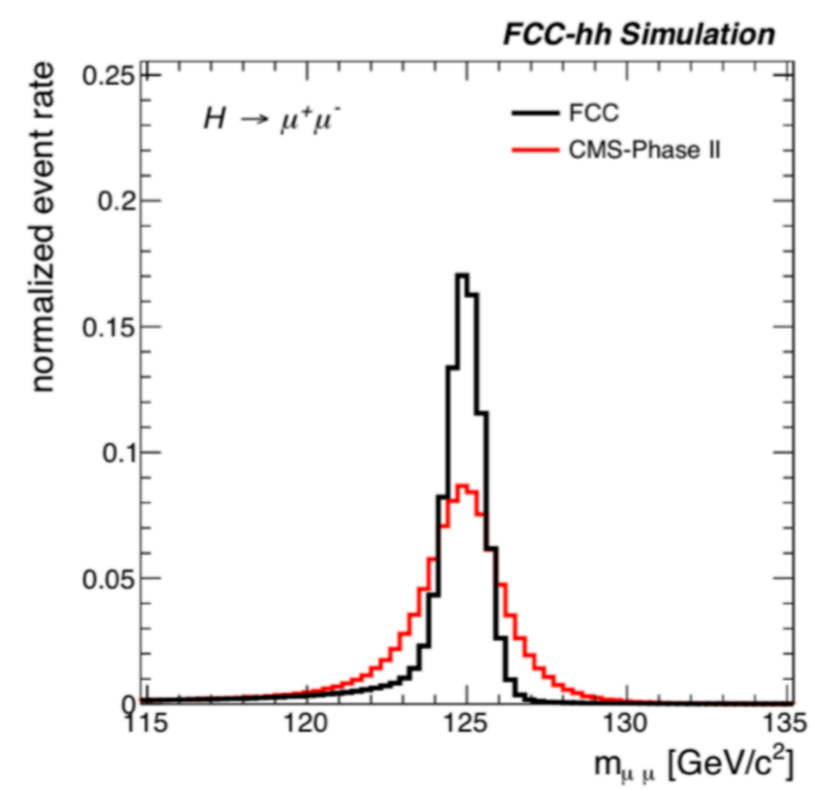


SM Physics produced at threshold is <u>more forward</u> @100TeV

→ in order to maintain sensitivity need **large rapidity** (with tracking) and **low p_T** coverage







low p_T muons → resolution dominated by MS

- <u>Goals:</u>
  - **Precision spectroscopy** and calorimetry up to **$|\eta| < 4$**
  - Tracking and calorimetry up to $|\eta| < 6$

Why measuring Higgs at high energy pp colliders?

- High energy pp provides **unique and complementary measurements** to ee colliders:
  - Higgs **self-coupling**
  - **top Yukawa**
  - **Higgs → invisible**
  - **rare decays** (BR(μμ), BR(Zɣ), ratios, ..) measurements will be **statistically limited** at FCC-ee

	HL-LHC	FCC-ee
$\delta\Gamma_H / \Gamma_H$ (%)	SM	1.3
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	0.17
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	0.43
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	0.61
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	1.21
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	1.01
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	0.74
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–
$\delta g_{HHH} / g_{HHH}$ (%)	50	40
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	< 1%

Need to improve

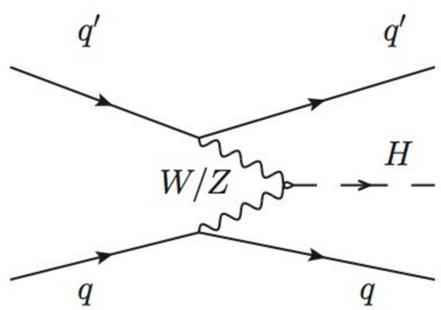
$$BR(H \to XX) / BR(H \to ZZ) \approx g_X^{\,2} / g_Z^{\,2}$$

from e^+e^-

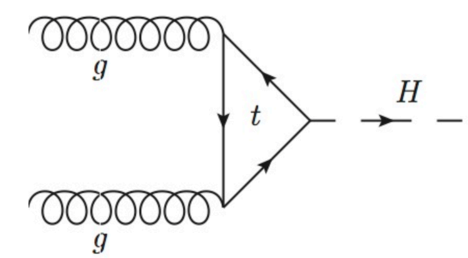
Large rates for rare modes and HH production at FCC-hh

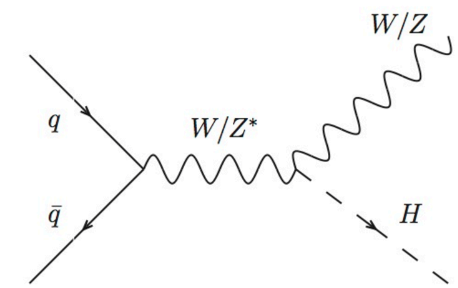
→ complementary to e^+e^-

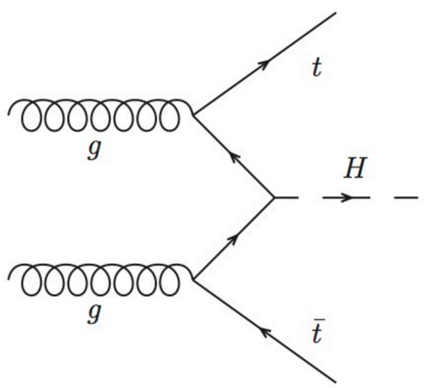
Single Higgs production @FCC-hh



	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N^3LO)	49 pb	803 pb	16
VBF (N^2LO)	3.8 pb	69 pb	16
VH (N^2LO)	2.3 pb	27 pb	11
ttH (N^2LO)	0.5 pb	34 pb	55







$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 20\ \mathrm{ab}^{-1}$

$N_{8} = \sigma_{8\,\mathrm{TeV}} \times 20\ \mathrm{fb}^{-1}$

$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

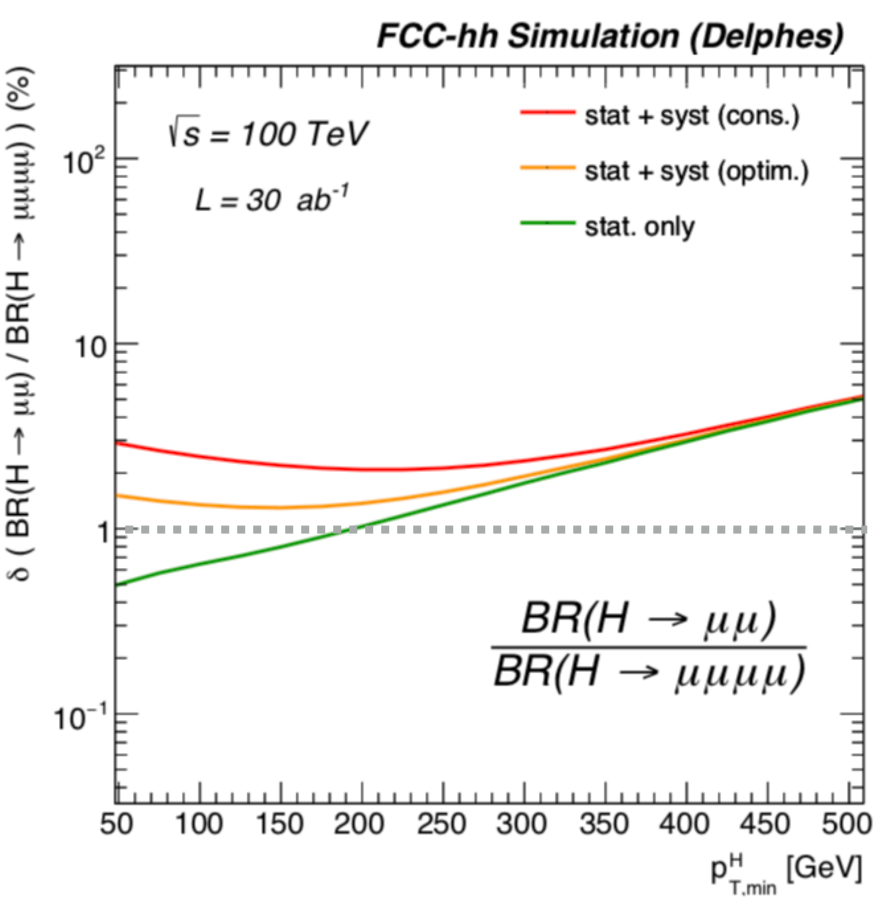
- Improvement factor on stat. unc.:
  - **3-5** at **27 TeV** vs HL-LHC
  - **10** at **100 TeV** vs HL-LHC

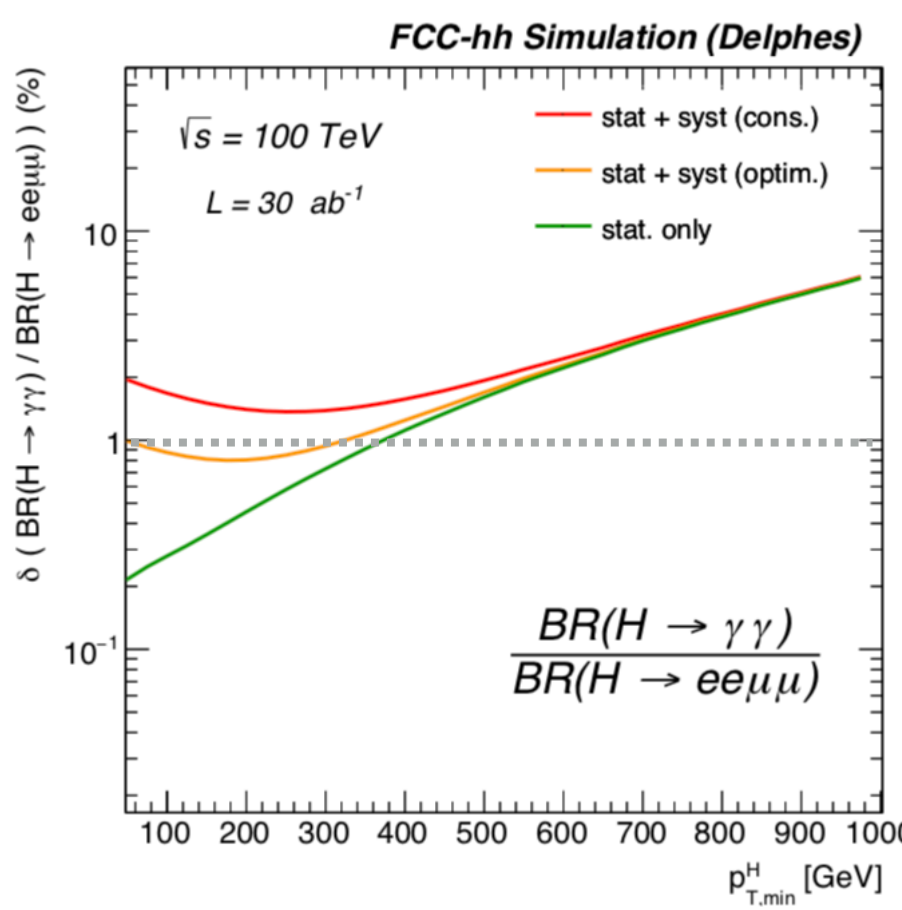
Large statistics in various Higgs decay modes allow:

- for % **- level precision in statistically limited** rare channels (μμ, Zɣ)
- in **systematics limited** channels, to isolate **cleaner samples** in regions (e.g. @large Higgs p_T) with :
  - higher S/B
  - smaller (relative) impact of systematic uncertainties

Ratios of BR(H→XX) / BR(H→ZZ)

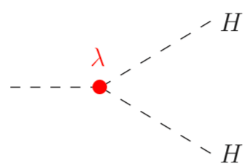
- measure **ratios of BRs** to cancel correlated sources of systematics:
  - luminosity
  - object efficiencies
  - production cross-section (theory)
- Becomes **absolute precision** measurement in particular if combined with **H→ZZ** measurement from e^+e^- (at 0.2%)



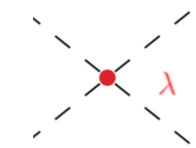


Sub-% level precision achievable on BR(H→μμ) and BR(H→γγ)

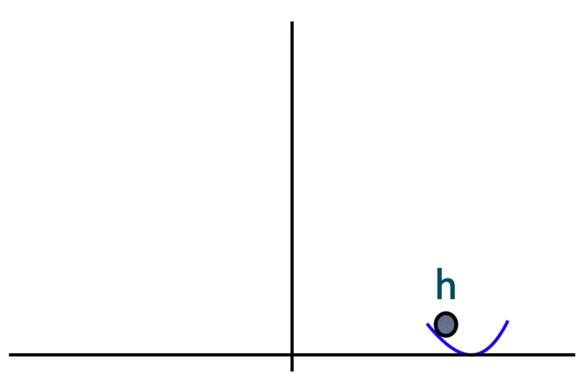
Why the Higgs self-coupling?

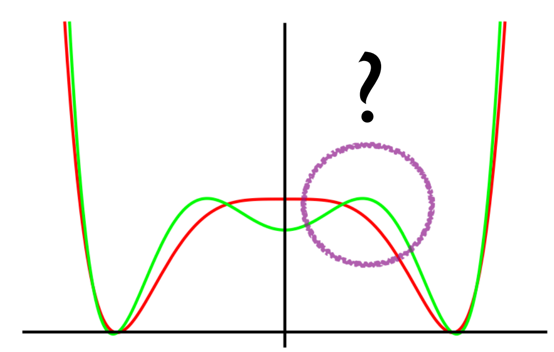


$$\mathcal{L}_h = m_h^2 h^2 + \lambda_3 h^3 + \lambda_4 h^4$$



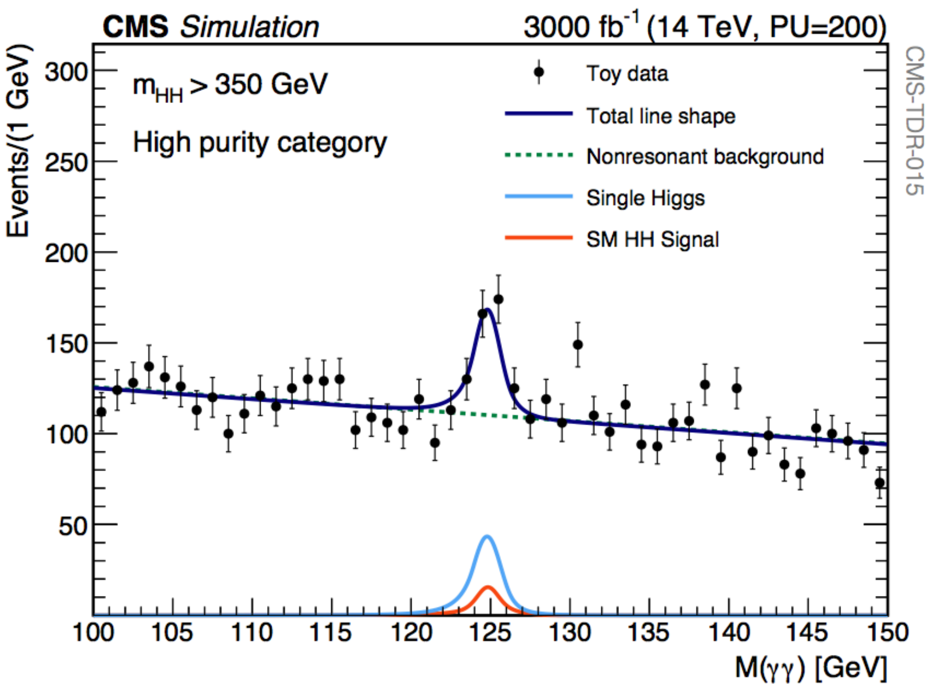
- In the SM, EWSB and λ_3 and λ_4 purely determined by the **shape of the Higgs potential**
- However, Higgs potential could be different (required by some scenarios of EWK baryogenesis) → **has barely been measured**
- Measuring the Higgs self-couplings gives a handle on the Higgs potential is determined by the self coupling value

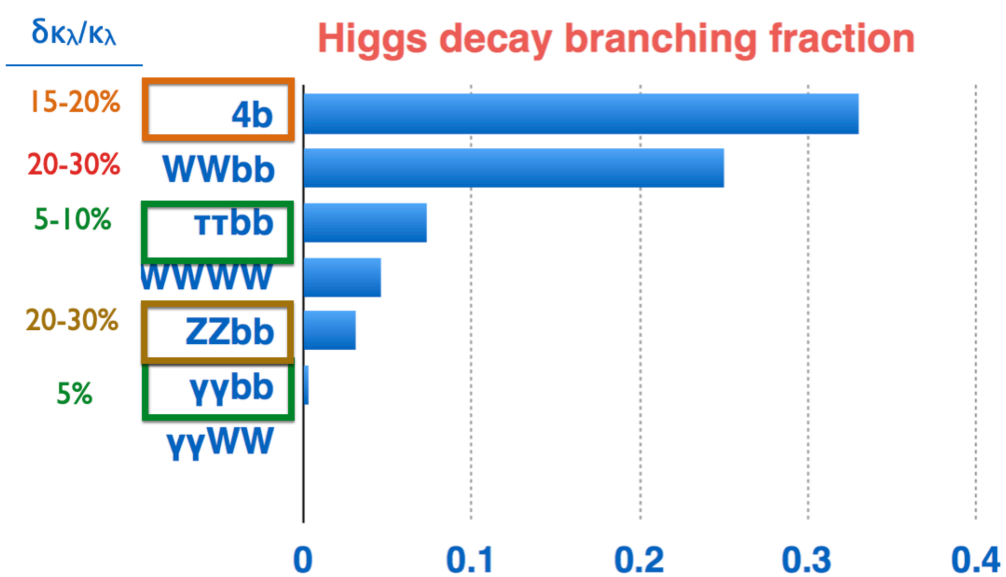




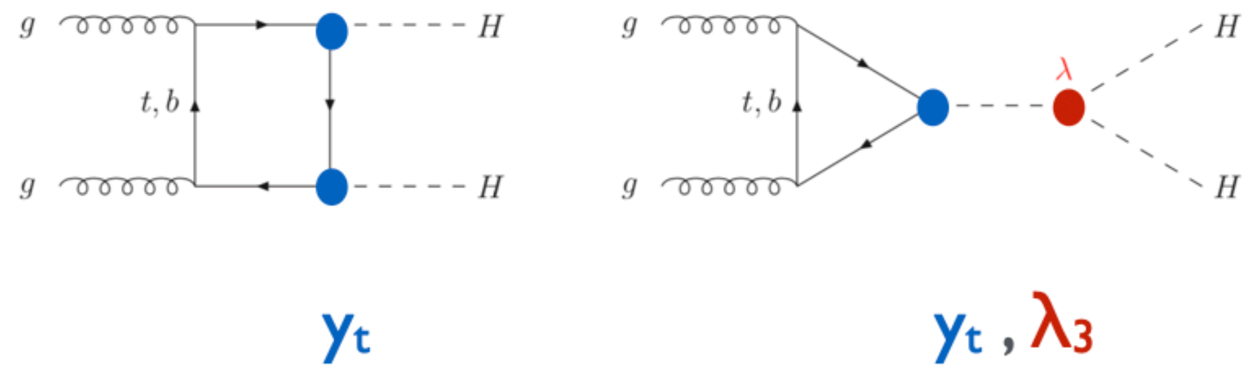
Higgs self-coupling

HL-LHC





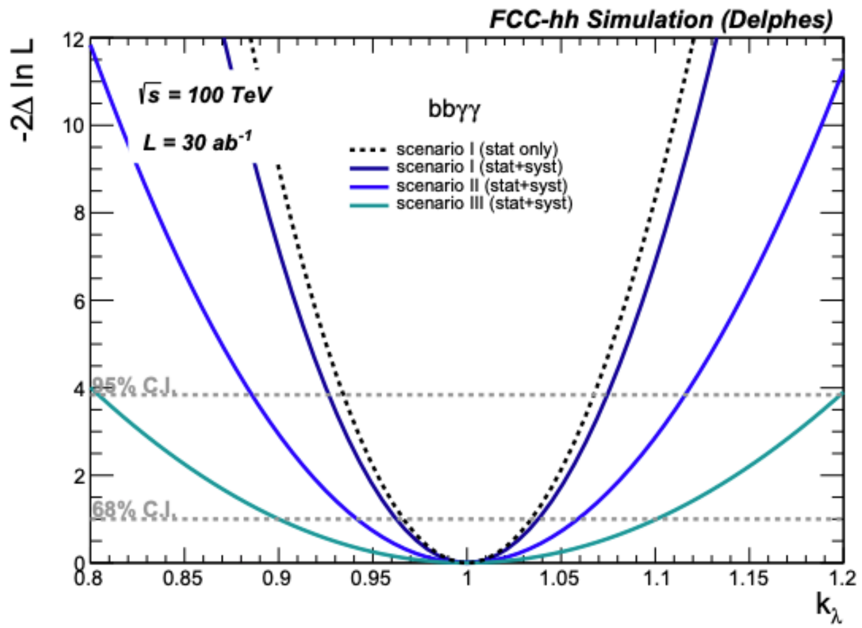
gluon fusion



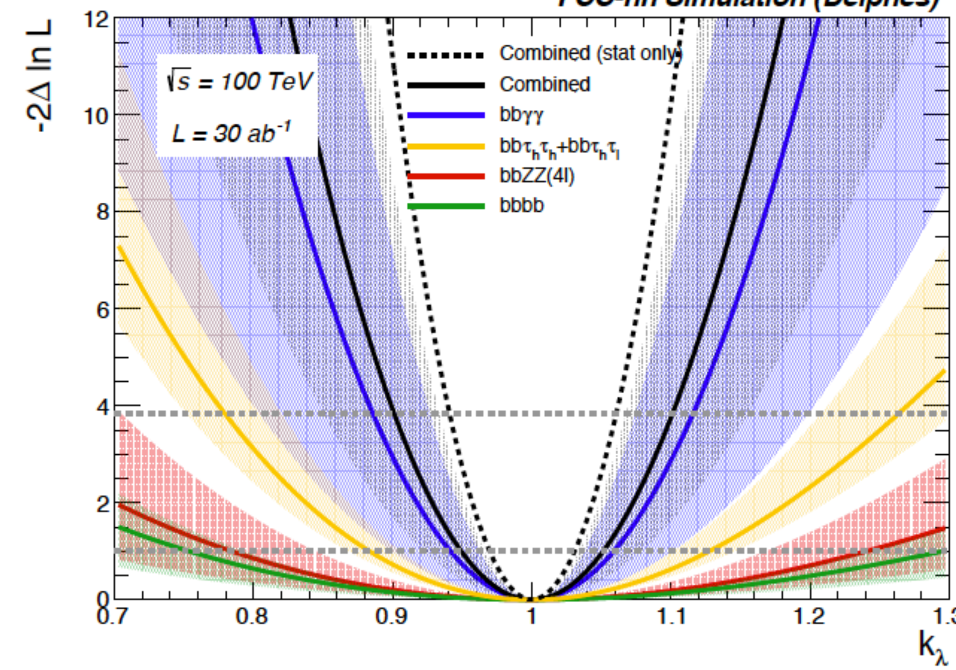
- Very small cross-section due to negative interference with box diagram
- HL-LHC projections : $\delta k_\lambda / k_\lambda \approx 50\%$
- Expect large improvement at high energy pp:
  - $\sigma(100\text{ TeV})/\sigma(14\text{ TeV}) \approx 40$ (and Lx10)
    - x400 in event yields and x20 in precision
  - $\sigma(27\text{ TeV})/\sigma(14\text{ TeV}) \approx 4$ (and Lx5)
    - x25 in event yields and x5 in precision

Self-coupling at future pp colliders

2004.03505 [hep-ph]

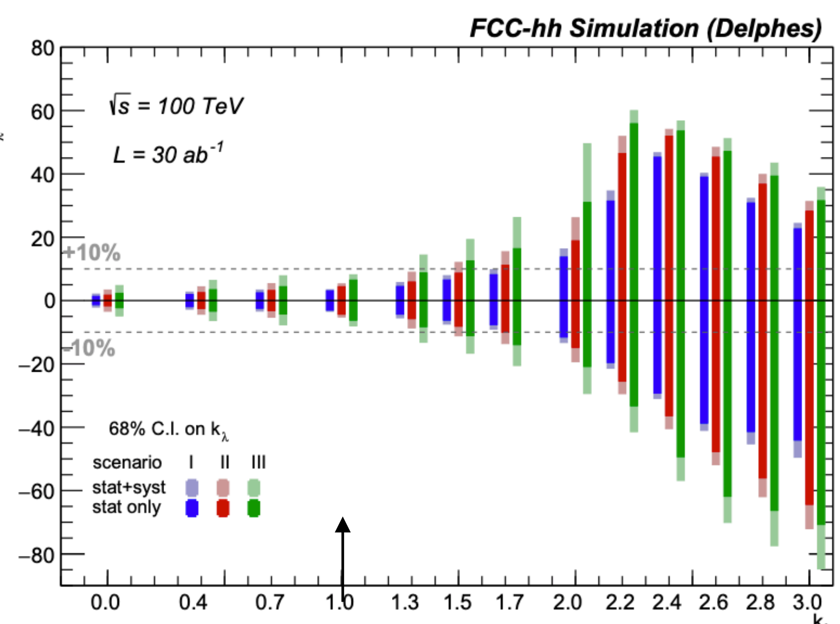


100 TeV



- Expected precision:

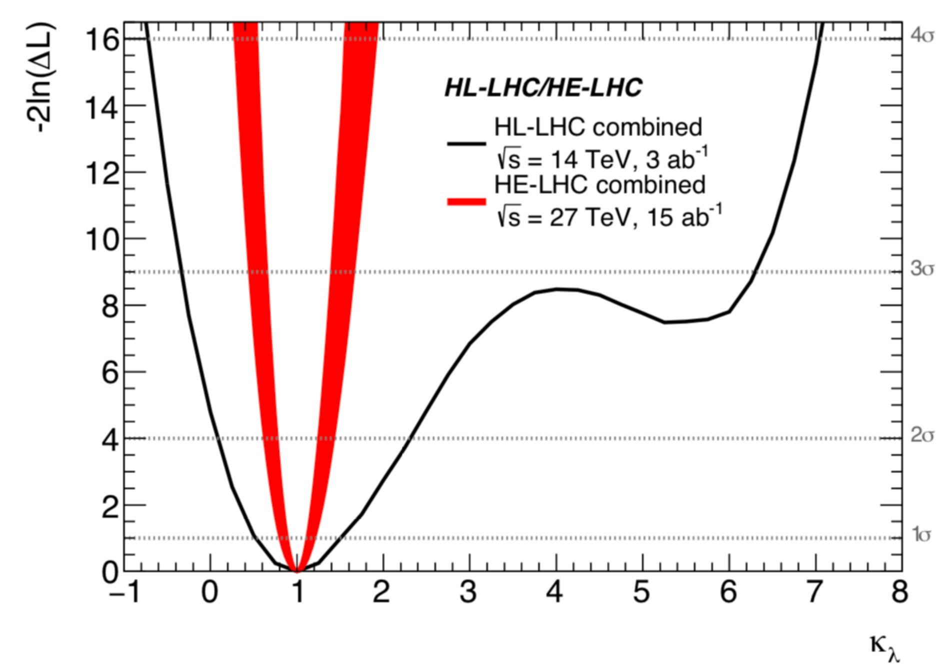
@68% CL	scenario I	scenario II	scenario III
bbγγ	3.8	5.9	10.0
bbττ	9.8	12.2	13.8
bbbb	22.3	27.1	32.0
comb.	3.4	5.1	7.8



SM

- Combined precision (100 TeV):
  - 3.5-8% for SM (100 TeV)
  - **10-20%** for $\lambda_3 = 1.5 * \lambda_3^{SM}$

27 TeV



- Combined precision:
  - 10-20% for SM (27 TeV)

Summary of Higgs direct measurements

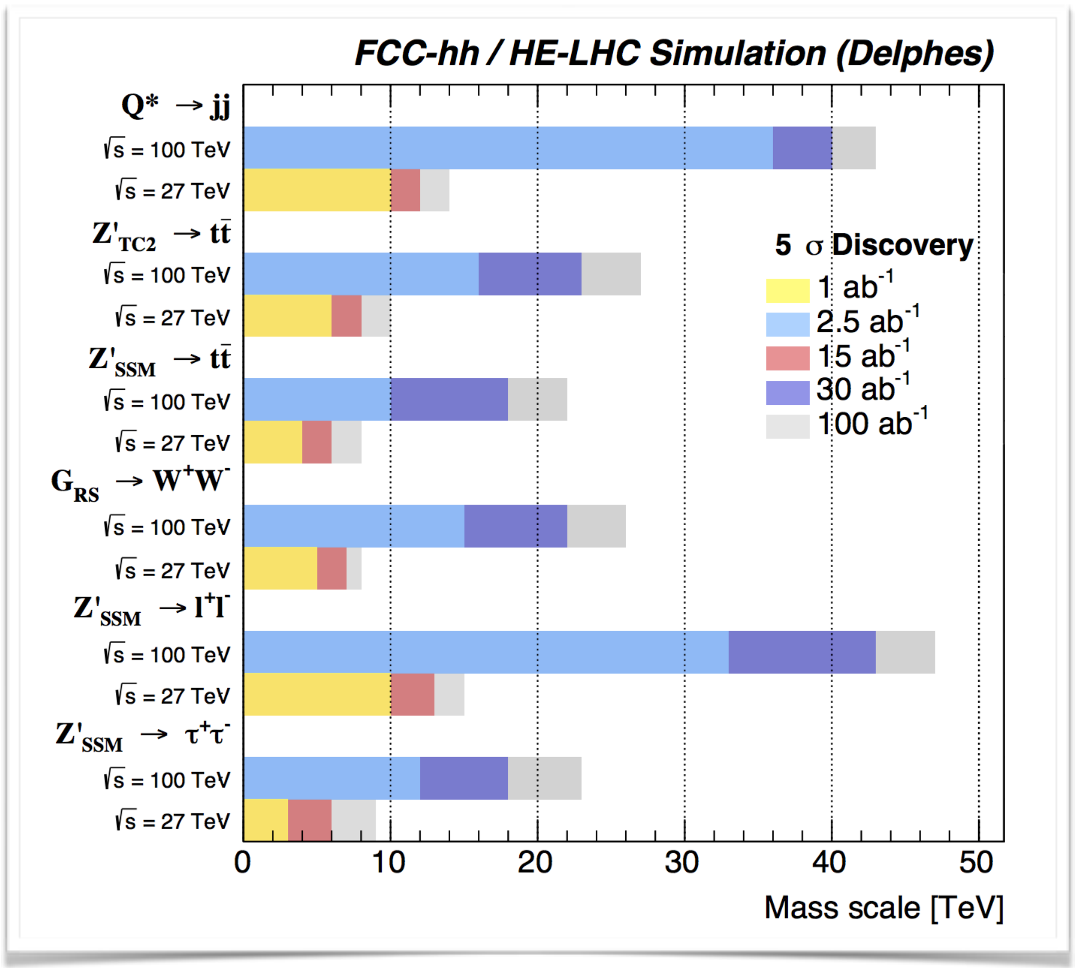
Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(\mathrm{H})\times \mathrm{B}(\mathrm{H}\to \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$R = \mathrm{B}(\mathrm{H}\to \mu\mu)/\mathrm{B}(\mathrm{H}\to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = \mathrm{B}(\mathrm{H}\to \gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = \mathrm{B}(\mathrm{H}\to \gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = \mathrm{B}(\mathrm{H}\to \mu\mu\gamma)/\mathrm{B}(\mathrm{H}\to \mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(\mathrm{t\bar{t}H})\times \mathrm{B}(\mathrm{H}\to \mathrm{b\bar{b}})/\sigma(\mathrm{t\bar{t}Z})\times\mathrm{B}(\mathrm{Z}\to \mathrm{b\bar{b}})$	$\delta R/R$	1.05%	1.9%
$B(\mathrm{H}\to$ invisible)	B@95%CL	1×10^{-4}	2.5×10^{-4}
HH production	$\delta\lambda/\lambda$	3.0–5.6%	3.4–7.8%

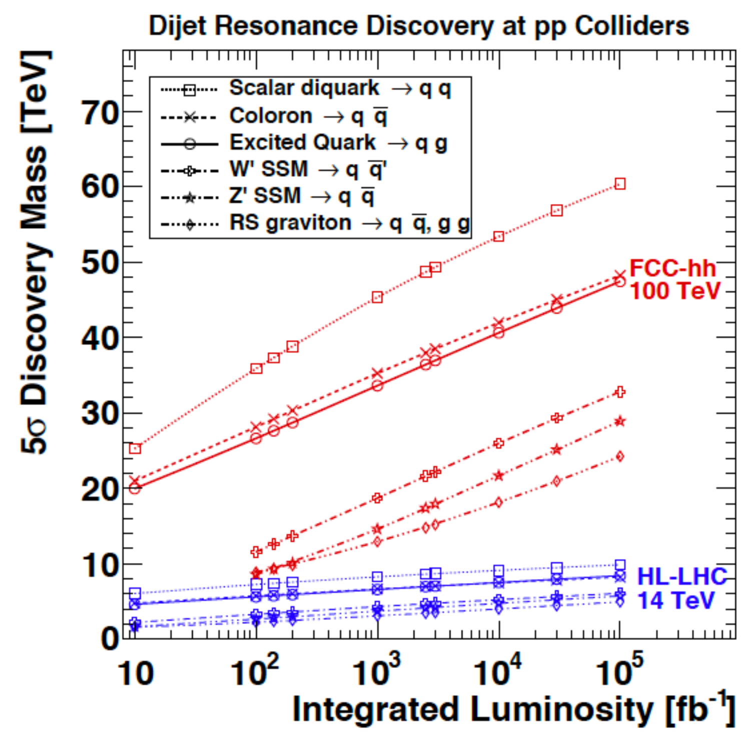
also in [2203.06520]

$\delta R/R$	HE-LHC	LE-FCC	FCC-hh
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2e2\mu)$	1.7%	1.5%	0.8%
$R = \mathrm{B}(\mathrm{H}\to\mu\mu)/\mathrm{B}(\mathrm{H}\to 4\mu)$	3.6%	2.9%	1.3%
$R = \mathrm{B}(\mathrm{H}\to\mu\mu\gamma)/\mathrm{B}(\mathrm{H}\to\mu\mu)$	8.4%	6%	1.8%
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2\mu)$	3.5 %	2.8%	1.4%

- **Percent level precision on σ x BR** in most rare decay channels achievable only at 100 TeV
- **Percent level precision on couplings** if HZZ coupling known from FCC-ee (to 0.2%)

Heavy resonances high energy pp





Model	HL-LHC $\sqrt{s}$ = 14 TeV, $\int Ldt$ = 3 ab^{-1} 5σ [TeV]	95% CL [TeV]	FCC-hh $\sqrt{s}$ = 100 TeV, $\int Ldt$ = 30 ab^{-1} 5σ [TeV]	95% CL [TeV]
Strongly Produced Dijet Resonances				
Diquark	8.7	9.4	57	63
Coloron	7.1	7.8	45	51
q*	7.0	7.9	44	50
Weakly Produced Dijet Resonances				
W'	4.8	5.6	29	36
Z'	4.2	5.2	25	32
RS grav.	3.5	4.4	21	27
Top Squark $\tilde{t}_1\tilde{t}_1 \to (t\,\tilde{\chi}_1^0)\,(t\,\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)=0$				
$\tilde{t}_1$	1.3	1.7	9.6	10.8

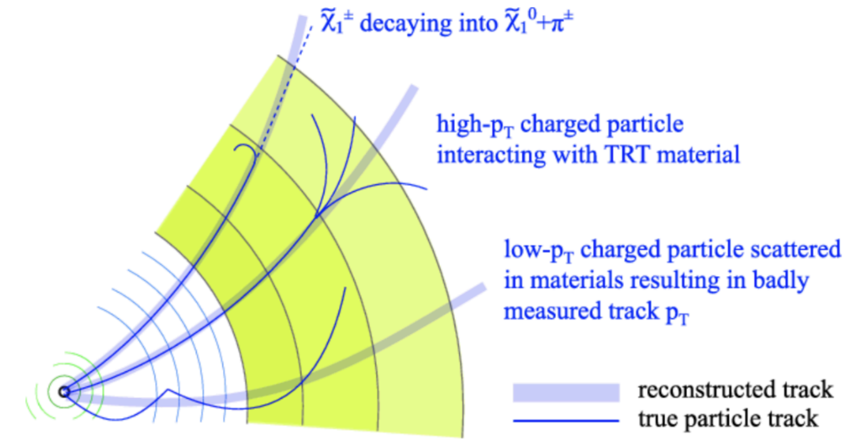
also in [2202.03389]

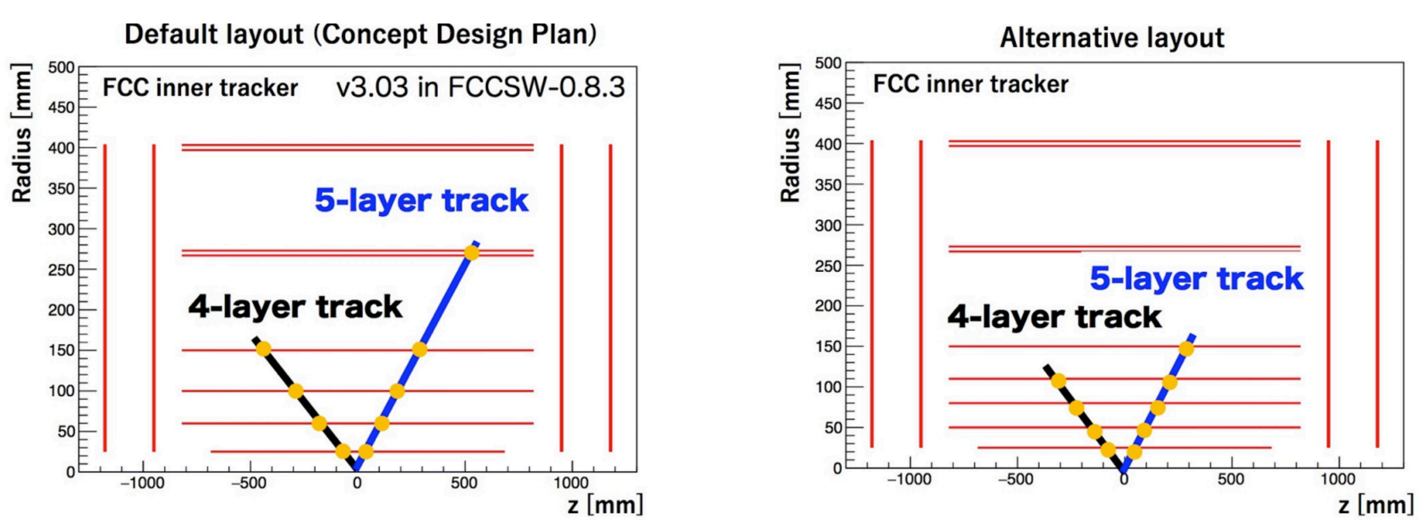
- High mass resonances Z → ee/ μμ / j j / tt … reach should scale as √s/14 TeV
- Provide crucial benchmarks for optimising detector design:
  - High momentum tracks and muons
  - Boosted hadronic signatures …

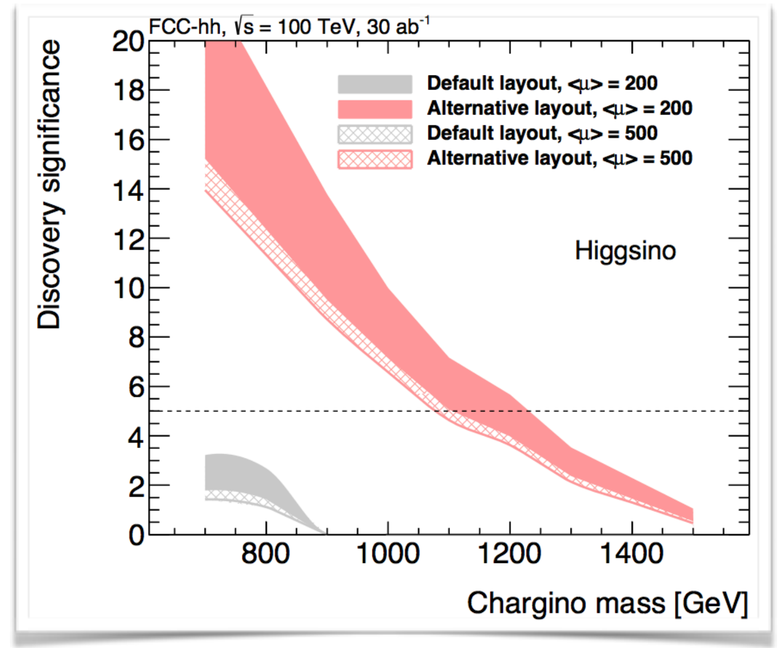
WIMPs/Disappearing tracks

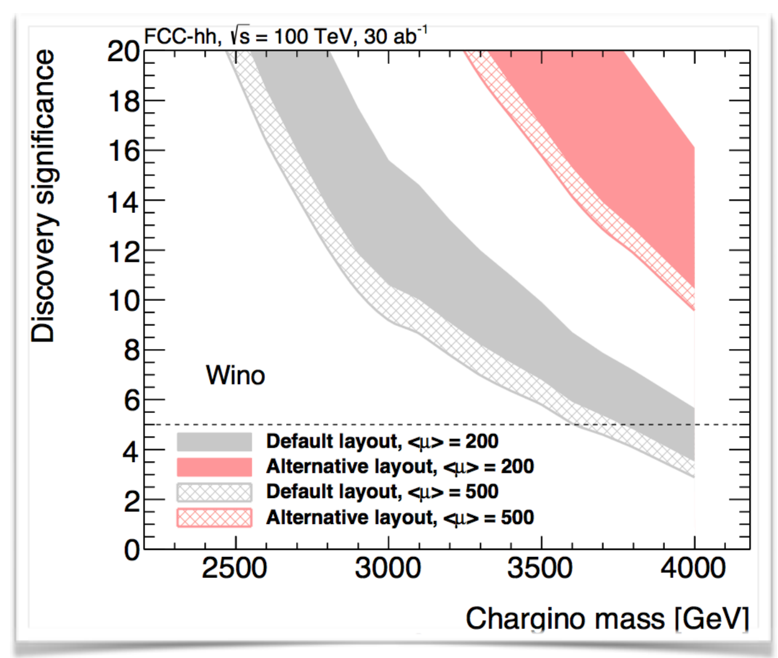
- Observed relic density of Dark Matter Higgsino-like: 1TeV, Wino-like: 3TeV
  - Mass degeneracy: wino 170MeV, Higgsino 350MeV
- Wino/Higgsino LSP meta-stable chargino, cτ= 6cm(wino) 7mm(higgsino)

- Useful tools to optimise detector concepts

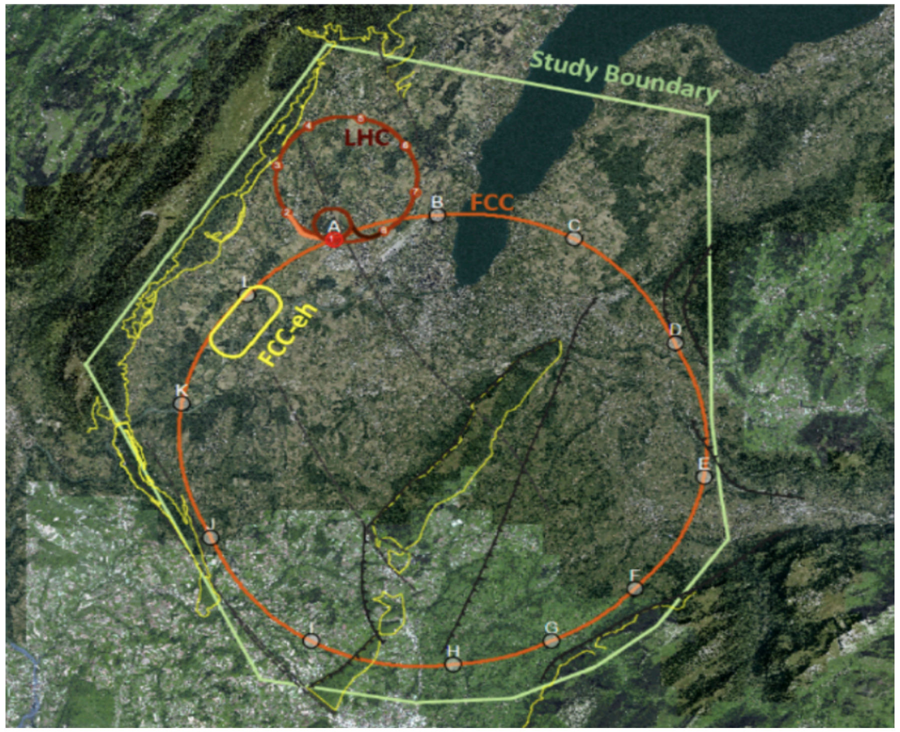






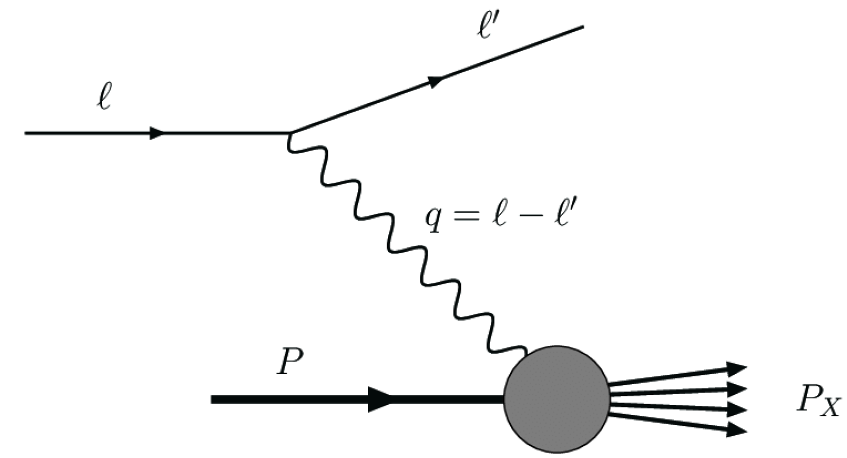


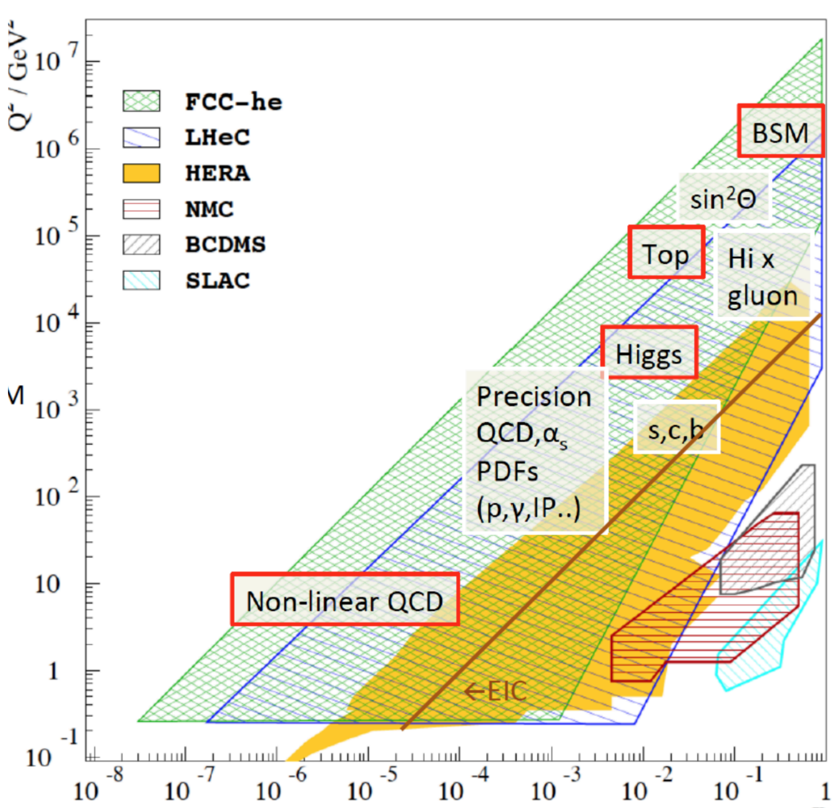
LHeC/FCC-eh



$e\,p \rightarrow \nu + X$

$e\,p \rightarrow e + X$

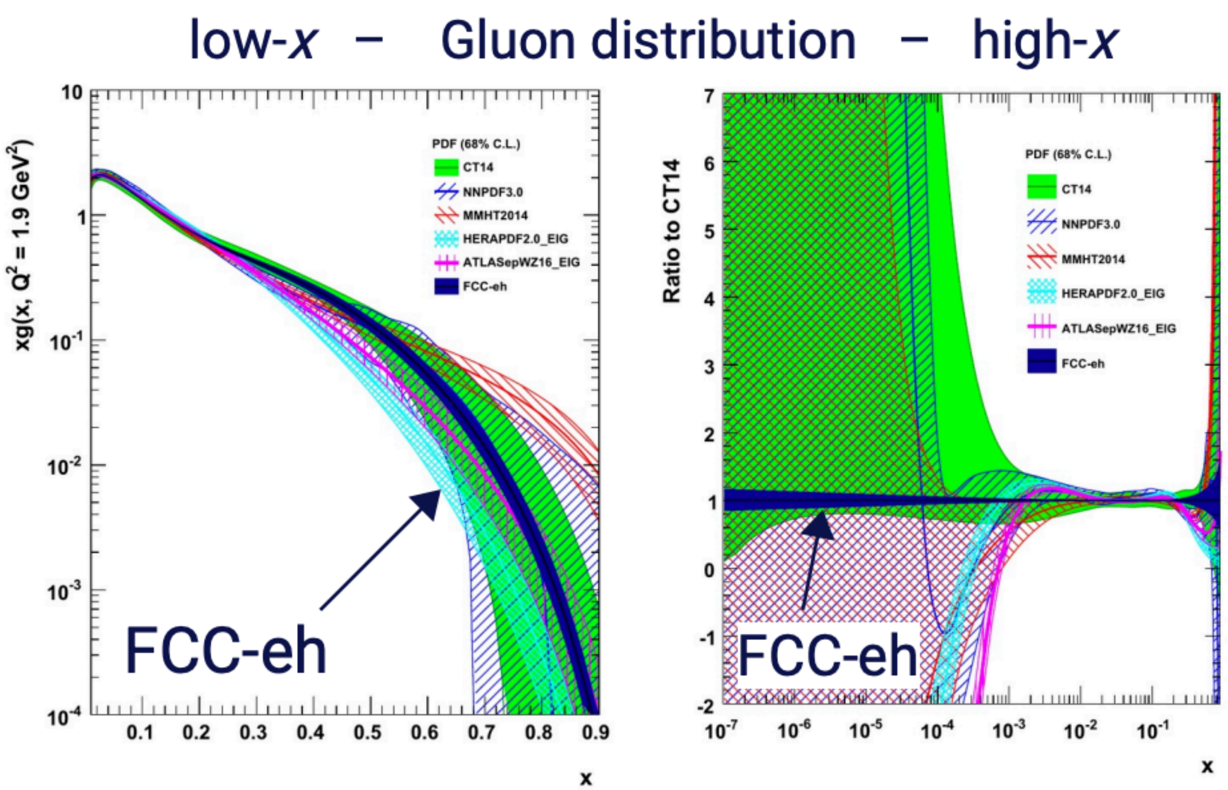




- Cleanest high resolution microscope
- Considerably extends HERA reach
- Rich physics programme:
  - SM:
    - QCD and proton/nuclear physics
    - Electro-weak (and anomalous couplings)
    - Top/FCNCs
    - Higgs
  - BSM:
    - Heavy neutrinos, ALPs

see [2007.14491]

LHeC/FCC-eh (QCD)

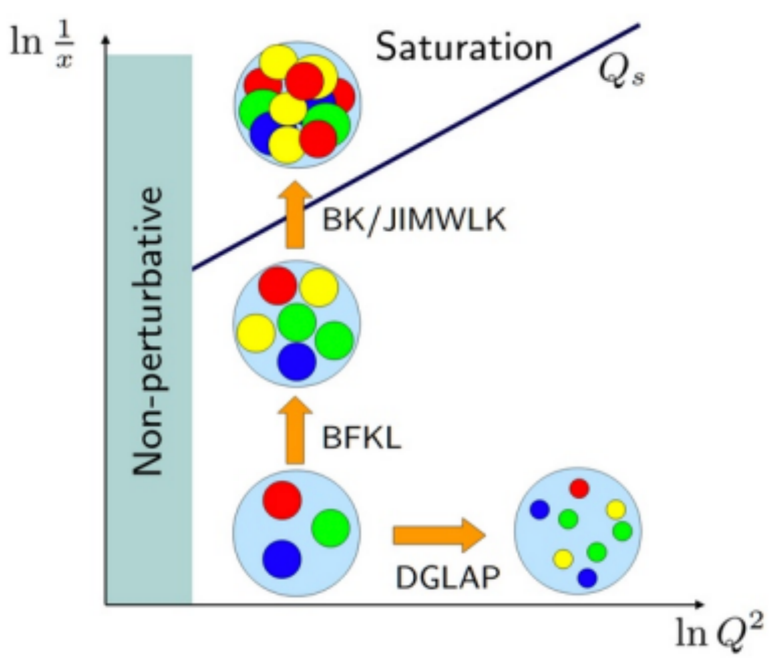


- Probe the proton structure with color neutral states

- Full determination of all parton flavour to unprecedented precision (low and high-x)

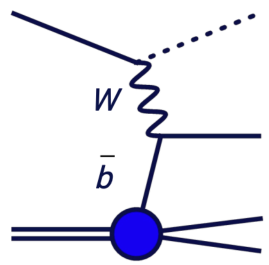
- Explore low-x regime :

  - Saturation?
  - Transverse Momentum Dependent (TMDs)
  - Generalized parton distribution functions (GPDs)

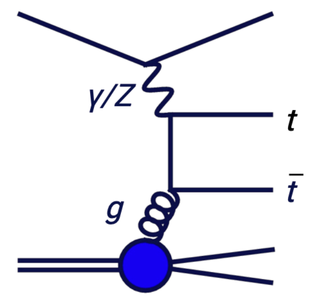


LHeC/FCC-eh (SM/Top/Higgs)

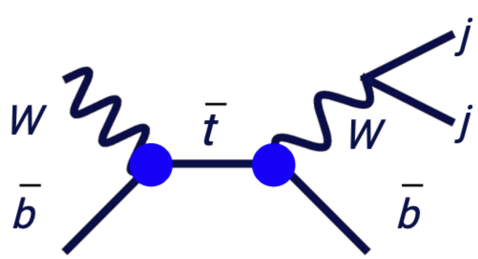
CC DIS single-top quark production



NC (γp) top-quark pair production



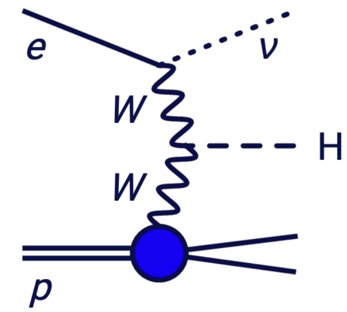
Direct measurement of V_{tb} from single top:



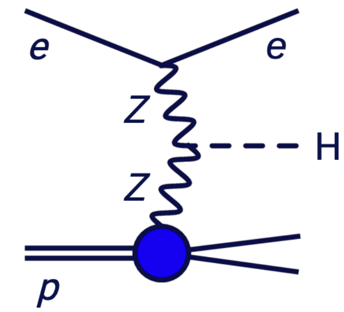
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad |V_{ts,td}|<0.04$$

Charged current

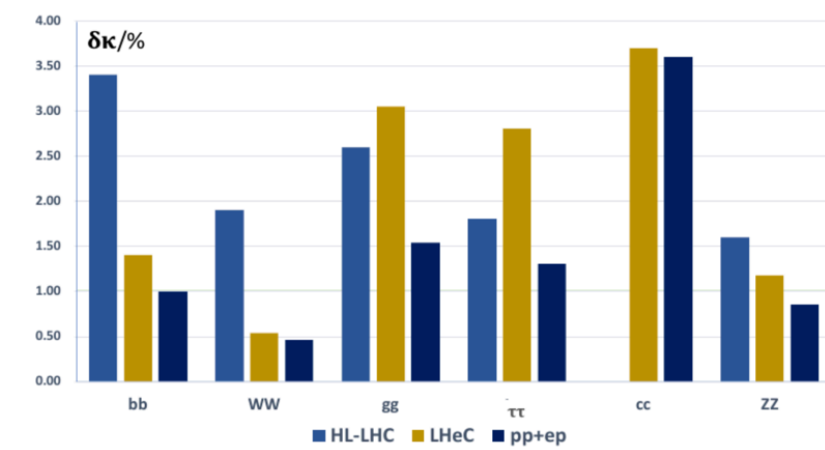


Neutral current



Interplay between *pp* and *ep*

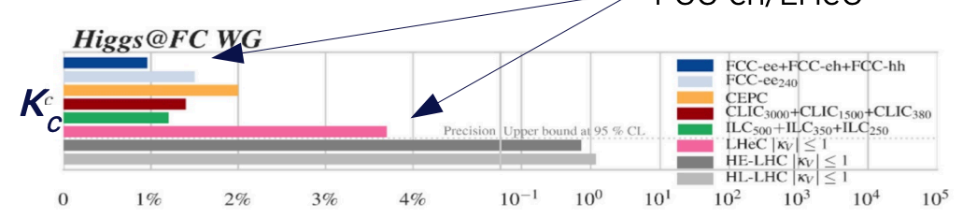
(shown here: LHeC & HL-LHC – similarly for FCC-hh/eh)



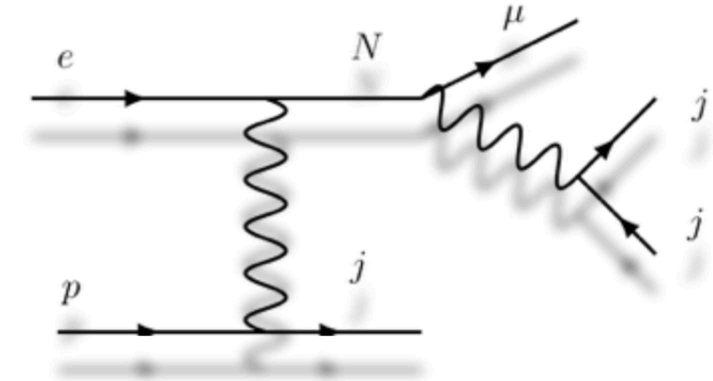
Complementarity between *pp* and *ep*

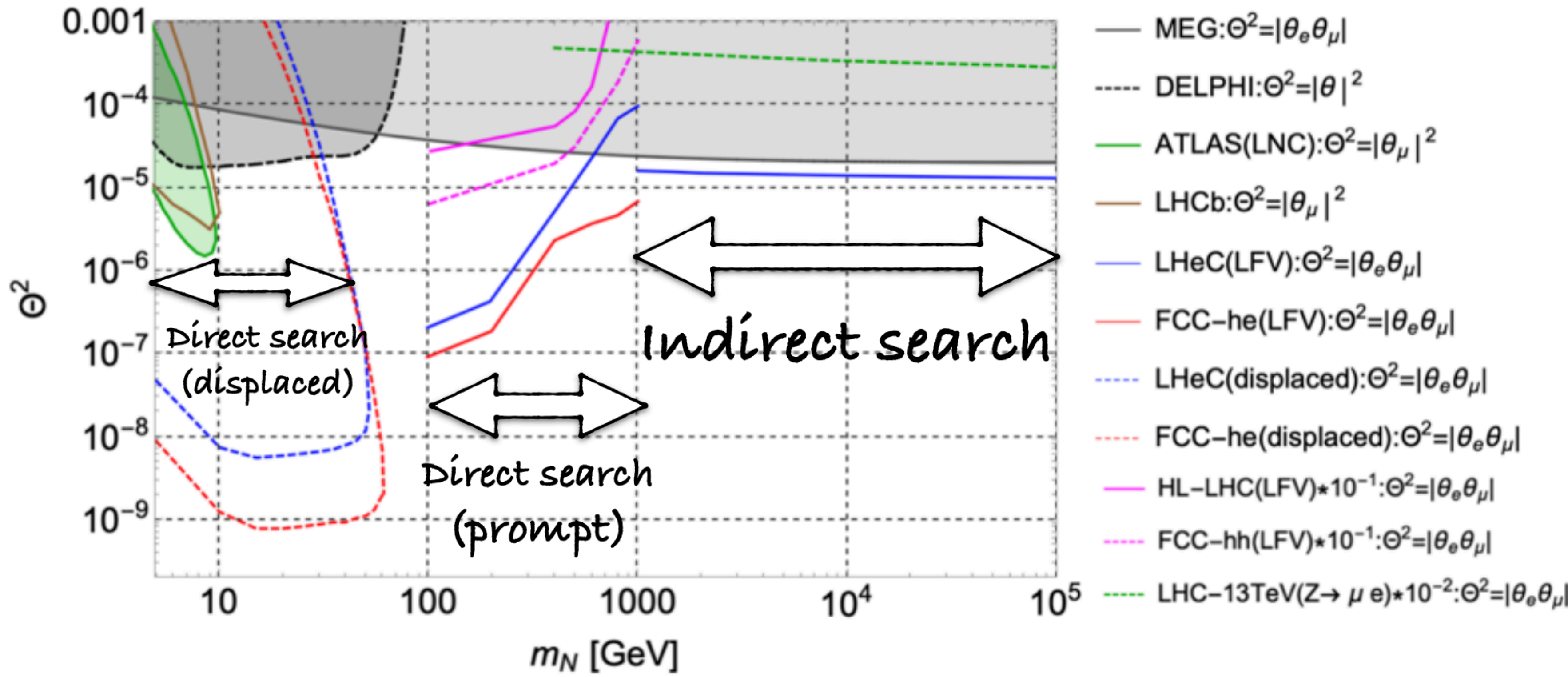
- *ep*: *bb, WW, ZZ, cc*
- *pp*: *gg, ττ, γγ*

FCC-eh/LHeC



LHeC/FCC-eh (BSM)





Highest reach for Heavy Neutral lepton searches (HNLs):

- long-lived
- prompt

- Rich BSM physics programme for FCC-eh
  - Lepton-quarks
  - LFV processes
  - Anomalous couplings
  - Contact interactions ….

Conclusions

- A next generation of accelerators is needed to study the Higgs sector and explore the energy frontier

- An LHeC/FCC-eh machine would provide excellent knowledge of the proton and complementary measurements to e+e- and high energy hh

- A high energy pp machine allows to further explore the unknowns:

  - Precisely measure Higgs properties (complementary couplings to Higgs factories)
  - Most precise exploration of the Higgs potential
  - Directly access WIMP dark matter
  - Access unknown unknowns …

Backup

Machine specs and detector requirements

lumi & pile-up

parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L} \times 10^{34}$	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mbarn	85	85	91	108
σ_{tot}	mbarn	111	111	126	153
BC rate	MHz	31.6	31.6	31.6	32.5
peak pp collision rate	GHz	0.85	4.25	22.8	32.4
peak av. PU events/BC		27	135	721	997
rms luminous region σ_z	mm	45	57	57	49
line PU density	mm^{-1}	0.2	0.9	5	8.1
time PU density	ps^{-1}	0.1	0.28	1.51	2.43
$dN_{ch}/d\eta\|_{\eta=0}$		7	7	8	9.6
charged tracks per collision N_{ch}		95	95	108	130
Rate of charged tracks	GHz	76	380	2500	4160
$<p_T>$	GeV/c	0.6	0.6	0.7	0.76
Number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm est.(FLUKA)	$\mathrm{GHz\,cm}^{-2}$	0.1	0.7	2.7	8.4 (12)
1 MeV-neq fluence at 2.5 cm est.(FLUKA)	$10^{16}\,\mathrm{cm}^{-2}$	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm est.(FLUKA)	MGy	1.3	13	54	270 (400)
$dE/d\eta\|_{\eta=5}$	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0

→ x6 HL-LHC

LHC: 30 PU events/bc
HL-LHC: 140 PU events/bc
FCC-hh: 1000 PU events/bc

but also x10 integrated luminosity w.r.t to HL-LHC

High granularity and precision timing needed to reduce occupancy levels and for pile-up rejection

Reach at high energies (I)

For more details see L.Wang lectures at IAS '17

To compute reach, we assume we need to observe given number of events:

$$N = \sigma \mathscr{L}$$

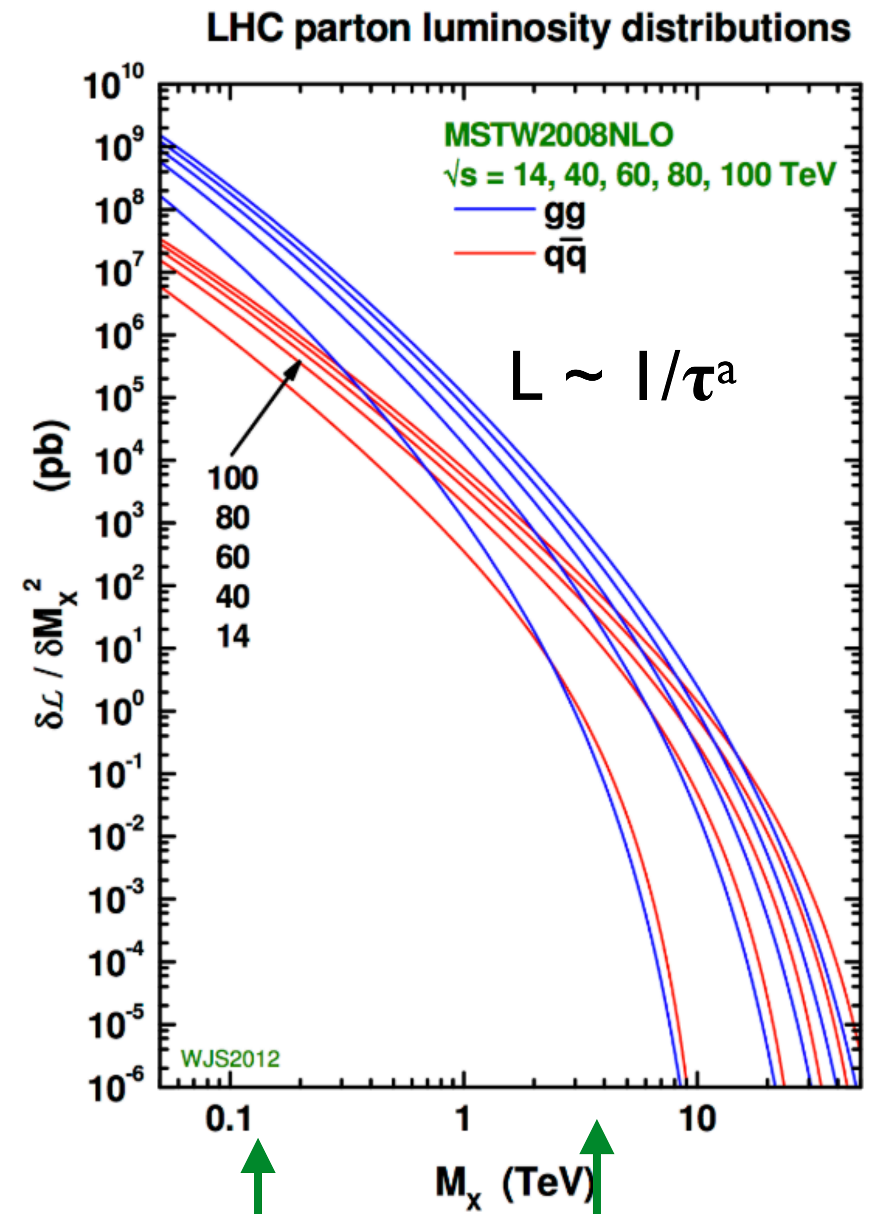
dimensional analysis

$$\sigma \sim L_{parton}(\tau) \cdot \sigma_{partonic}$$

$$1/\tau^{a} \qquad\qquad 1/M^2$$

$\tau = x_1 x_2 = M^2/s$

assumes mostly produce at threshold



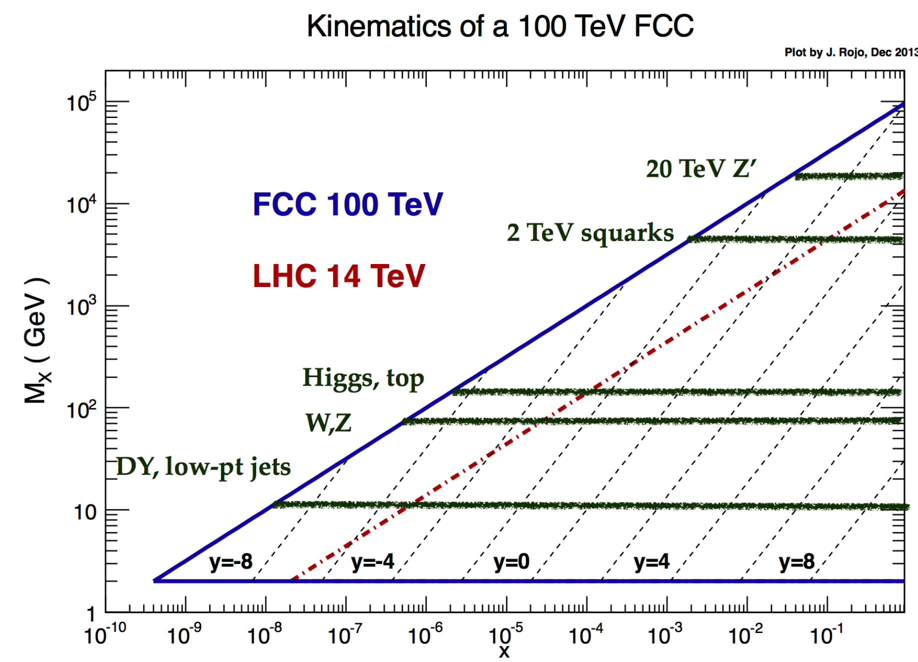
a≈2 a≈6

$\mathscr{L}$: integrated luminosity

L_{parton} : parton luminosity

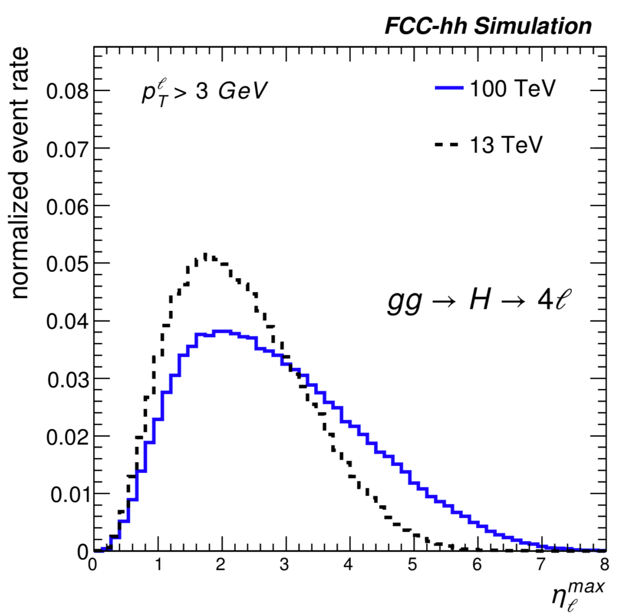
Higgs @threshold

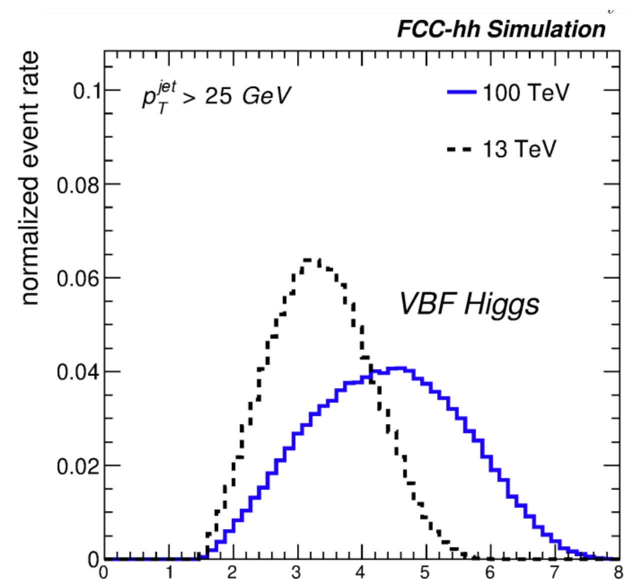
$x_{min} \sim M^2 / s$

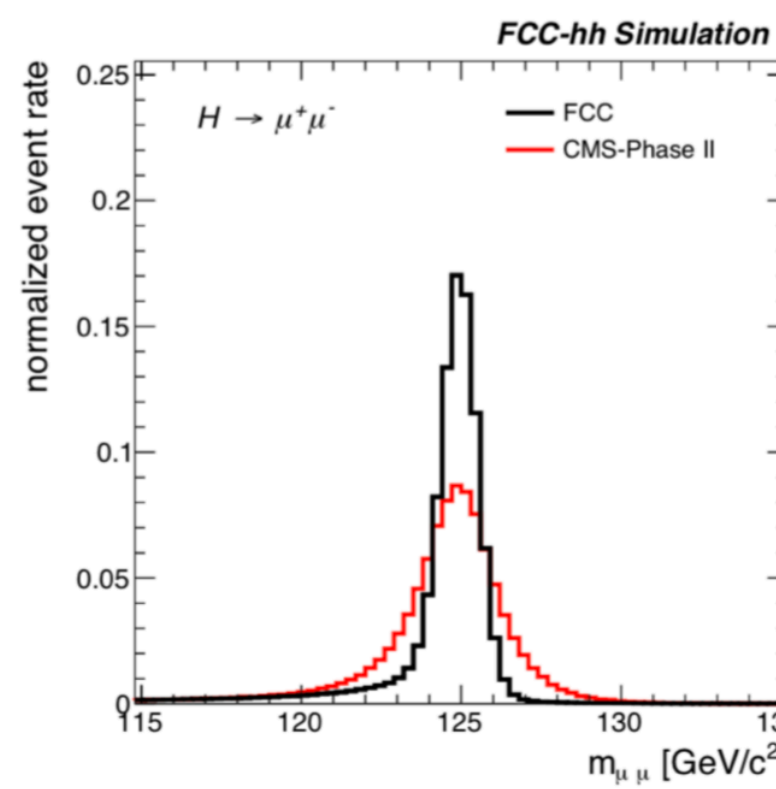


SM Physics produced at threshold is more forward @100TeV

→ in order to maintain sensitivity need **large rapidity** (with tracking) and **low p_T** coverage



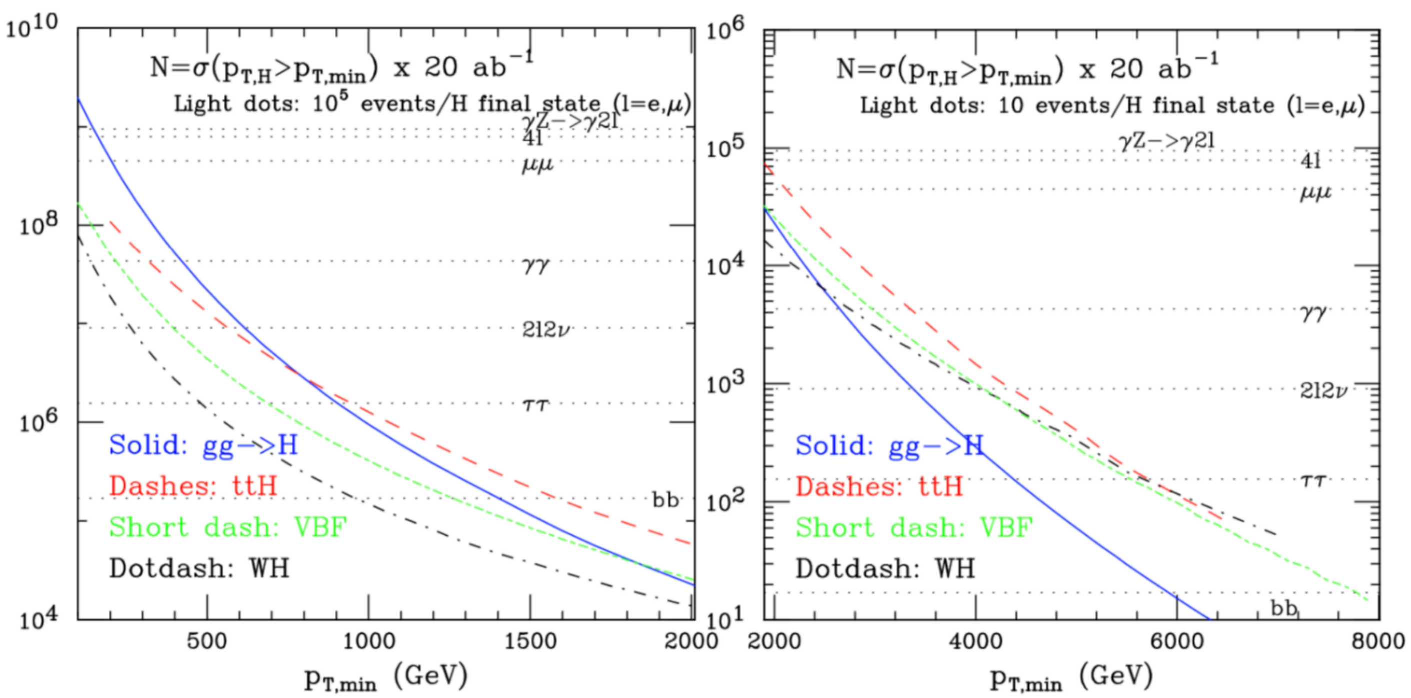




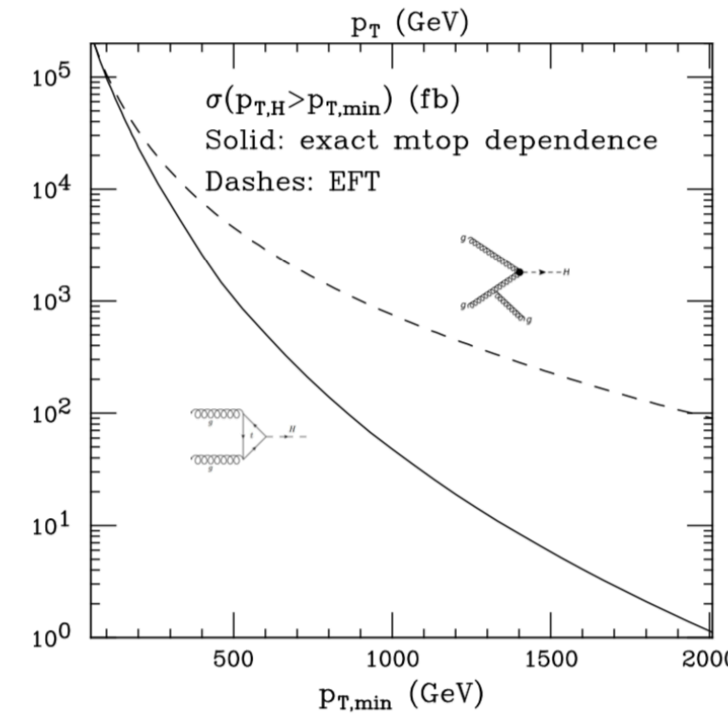
low p_T muons → resolution dominated by MS

- Goals:
  - **Precision spectroscopy** and calorimetry up to **|η| < 4**
  - Tracking and calorimetry up to |η| < 6

Higgs at large p_T



$N(p_T > p_{T,\,min})$

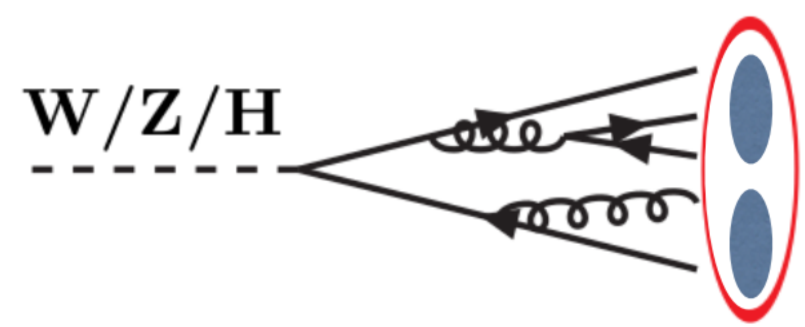


Huge rates at large p_T :

- **> 10⁶ Higgs** produced with p_T > 1 TeV
- Higher probability to produce large p_T Higgs from ttH/VBF/VH at large
- Even rare decay modes can be accessed at large p_T

Opportunity to measure the Higgs **in a new dynamical regime**

- Higgs p_T spectrum highly sensitive to new physics.



$\Delta R = 0.1$

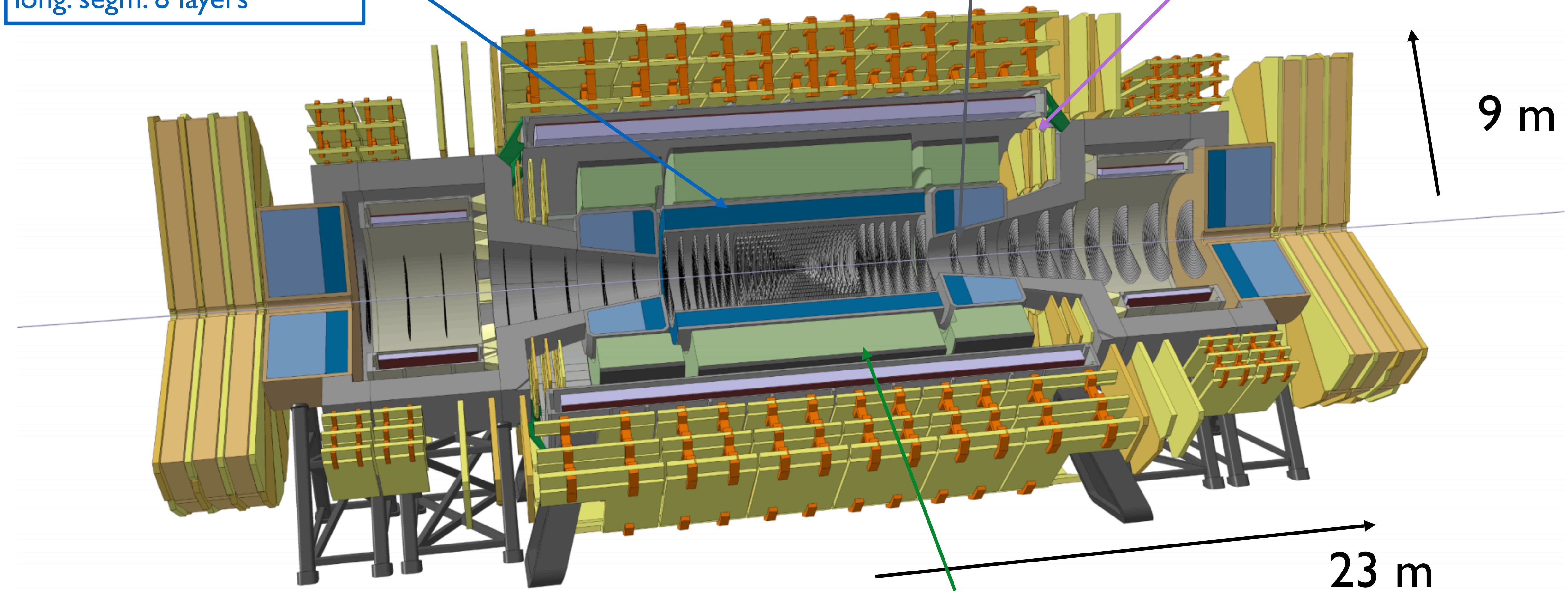
- highly granular sub-detectors:
  - Tracker - pixel:10 μm @ 2cm → $\sigma_{\eta\times\varphi} \approx$ 5 mrad
  - Calorimeters: 2 cm @ 2m → $\sigma_{\eta\times\varphi} \approx$ 10 mrad
- good energy/p_T resolution at large p_T:
  - σ_p / p = 2% @ 1 TeV

The FCC-hh detector

Tracker: $\sigma_{p_T}/p_T \sim 20\%$ at 10 TeV (1.5m radius)

Central Magnet + Fwd solenoids

Barrel ECAL: LAr/Pb
$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\ \%$
30 X_0
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 8 layers



Fwd ECAL: LAr/Cu
$\sigma_E/E \sim 30\%/\sqrt{E} \oplus 1\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 6 layers

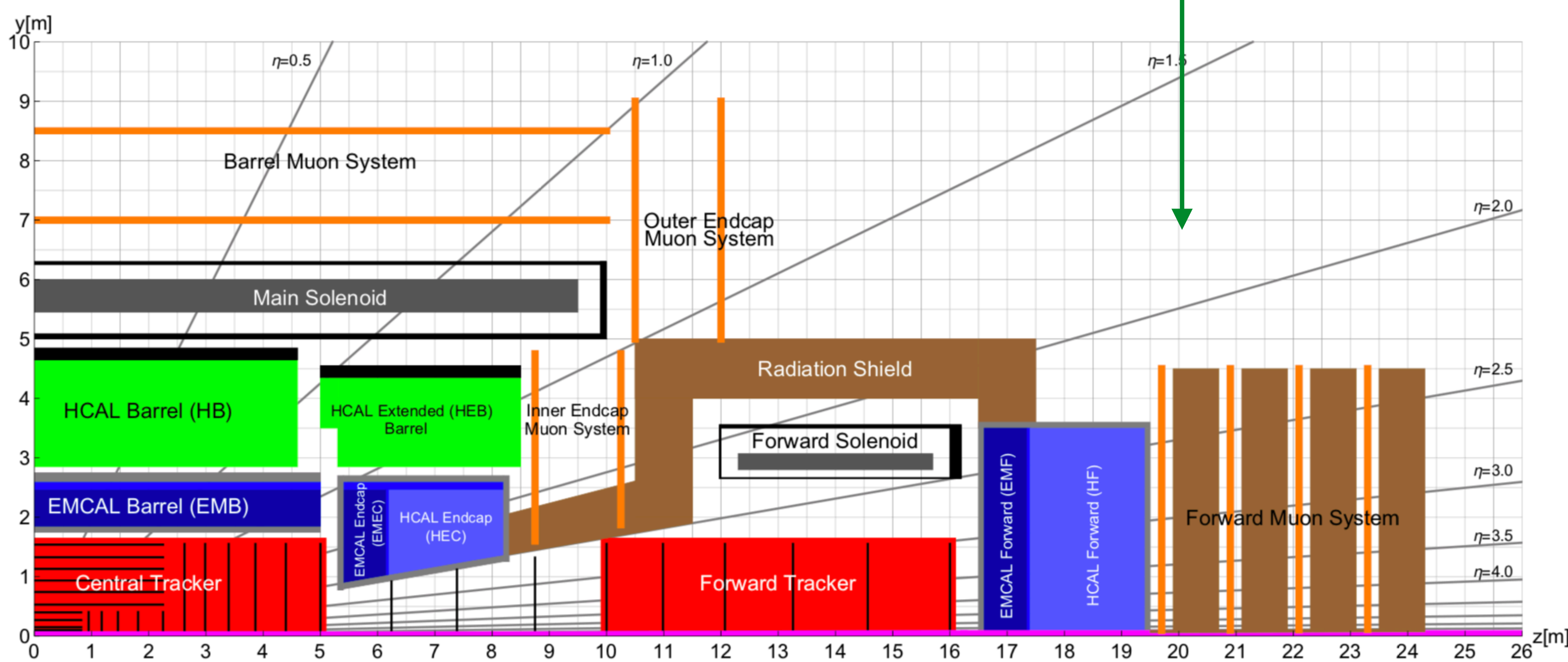
Fwd HCAL: LAr/Cu
$\sigma_E/E \sim 100\%/\sqrt{E} \oplus 10\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.05$
long. segm: 6 layers

Barrel HCAL: Sci/Pb/Fe
$\sigma_E/E \sim 50\text{-}60\%/\sqrt{E} \oplus 3\ \%$
11 λ (ECAL+HCAL)
lat. segm: $\Delta\eta\Delta\phi \approx 0.025$
long. segm: 10 layers

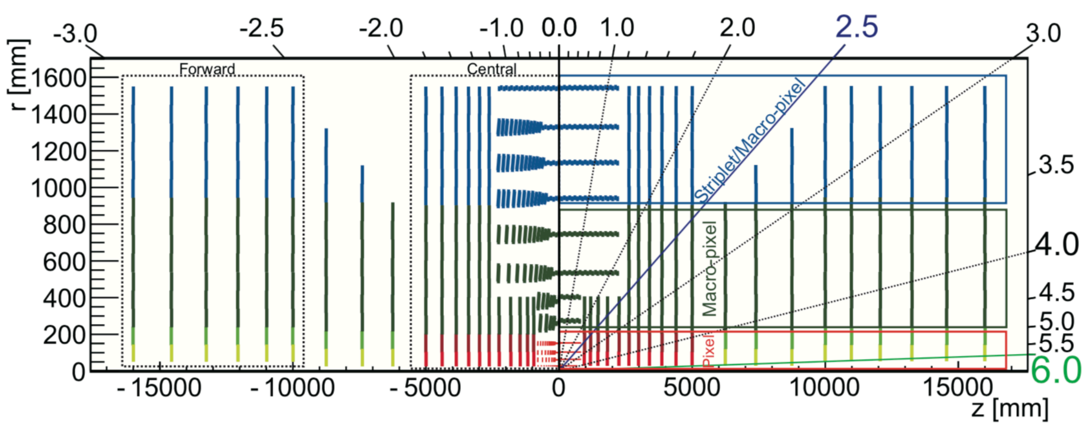
An FCC-hh detector

- Must be able to cope with:
  - very large dynamic range of signatures (E = 20 GeV -20 TeV)
  - hostile environment (1k pile-up and up to 10^{18} cm^{-2} MeV neq fluence)

- Characteristics:
  - large acceptance (for low p_T physics)
  - extreme granularity (for high p_T and pile-up rejection)
  - timing capabilities
  - radiation hardness



An FCC-hh detector that can do the job

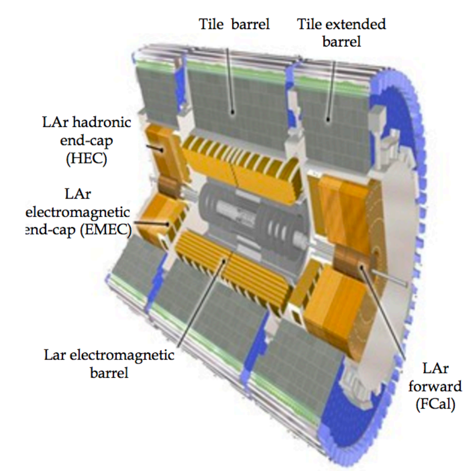


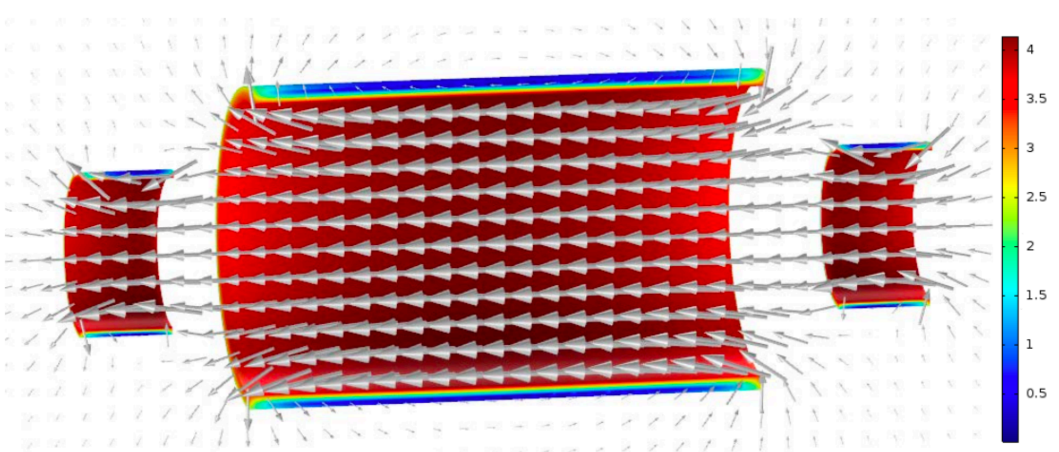
Tracker

- $-6 < \eta < 6$ coverage
- pixel : $\sigma_{r\phi}$ ~10µm, σ_Z ~15-30µm, X/X_0(layer) ~ 0.5-1.5%
- outer : $\sigma_{r\phi}$ ~10µm, σ_Z ~30-100µm, X/X_0(layer) ~ 1.5-3%

Calorimeters

- ECAL: LArg , $30X_0$, 1.6 λ, r = 1.7-2.7 m (barrel)
- HCAL: Fe/Sci , 9 λ, r = 2.8 - 4.8 m (barrel)



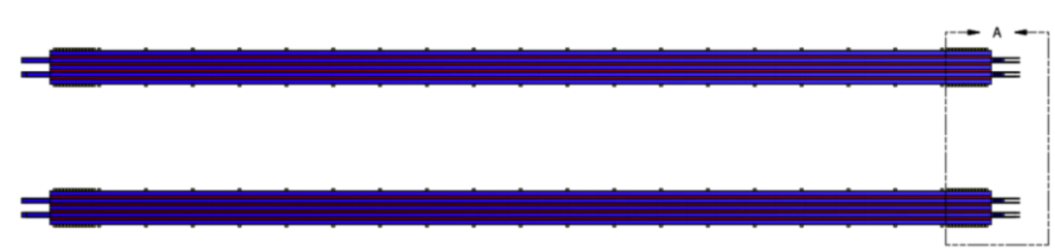


Magnet

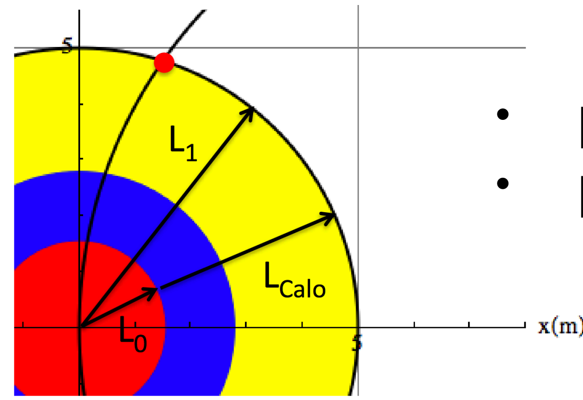
- central R = 5, L = 10 m, B = 4T
- forward R = 3m , L = 3m , B = 4T

Muon spectrometer

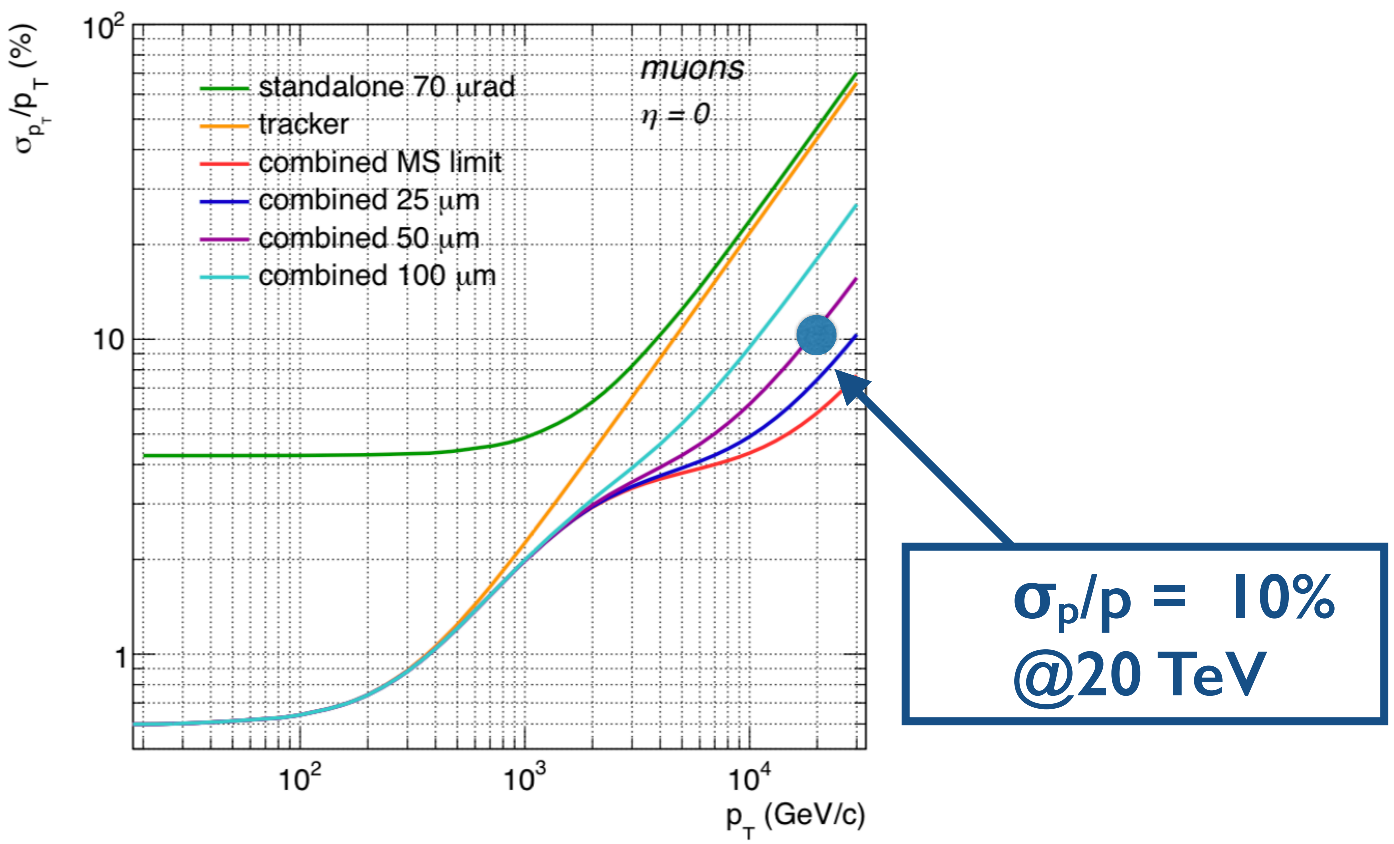
- Two stations separated by 1-2 m
- 50 µm pos., 70µrad angular

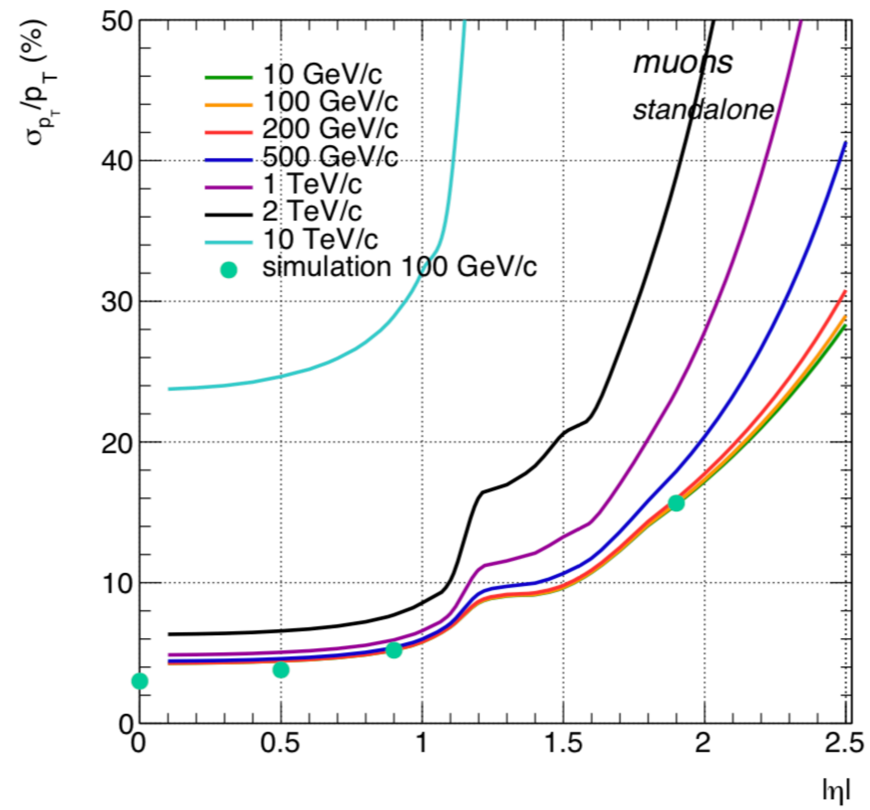


Muons



- pT = 4 GeV muons enter the muon system
- pT = 5.5 GeV leave coil at 45 degrees



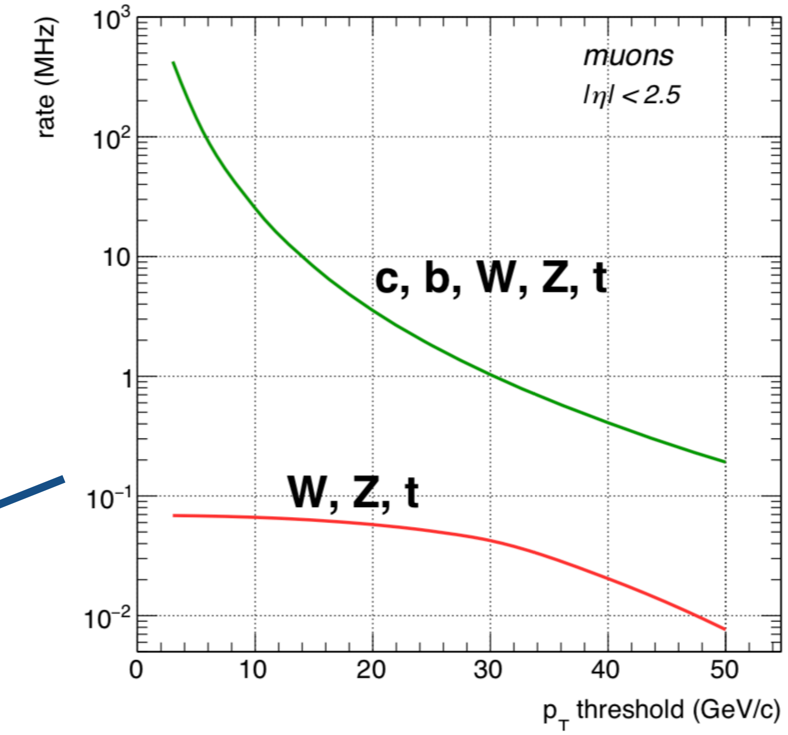


Calo + Coil = 180-280 X_0

- Standalone muon measurement with angle of track exiting the coil
- Target muon resolution can be easily achieved with 50 µm position resolution (combining with tracker)
- Good standalone resolution below |η| < 2.5
- Rates manageable with HL-LHC technology (sMDT)

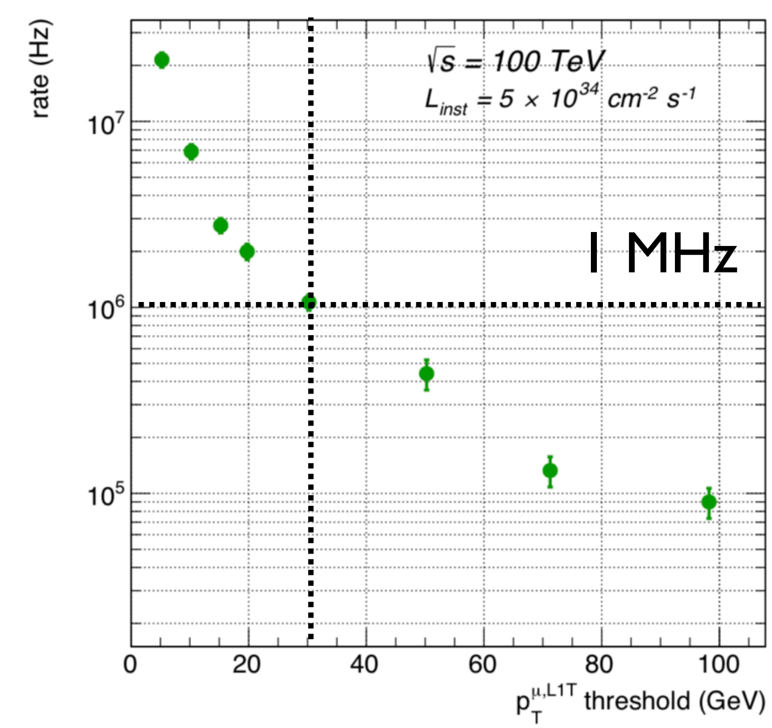
Data rates and trigger

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
$b\bar{b}$ cross-section	mb	0.5	0.5	1	2.5
$b\bar{b}$ rate	MHz	5	25	250	750
$b\bar{b}$ $p_T^b > 30$ GeV/c cross-section	μb	1.6	1.6	4.3	28
$b\bar{b}$ $p_T^b > 30$ GeV/c rate	MHz	0.02	0.08	1	8
Jets $p_T^{jet} > 50$ GeV/c cross-section [341]	μb	21	21	56	300
Jets $p_T^{jet} > 50$ GeV/c rate	MHz	0.2	1.1	14	90



Need more selectivity at Level 1 (full allocated PhaseII bandwidth for single muon pt > 30 GeV)!

- Phase II:
  - ATLAS/CMS calorimeters/muons readout @40MHz and sent via optical fibres to Level 1 trigger outside the cavern to create L1 trigger decisions (25 Tb/s)
  - Full detector readout @1MHz (@40MHz ~ 200 Tb/s)
- FCC-hh:
  - At FCC-hh Calo+Muon would correspond to 250 Tb/s (seems feasible)
  - However full detector would correspond to 1-2 Pb/s
    - Seems hardly feasible (30 yrs from now)
  - More selectivity needed @L1 (4D hit information?)



Strategy for R & D

- High profile R&d program needs to be carried on to make this possible, (leverage HL-LHC efforts)

- <u>Possible Directions:</u>

  - Radiation hard silicon detectors
  - High precision timing
  - Low power, high speed links
  - Highly segmented calorimeters (3D imaging calorimeters)
  - Software, reconstruction algorithms (4D particle-flow, boosted object tagging)
  - Large scale muon systems
  - Magnets
  - Cryogenics

CERN has released a document
On plans for R&D as input to
European Strategy:

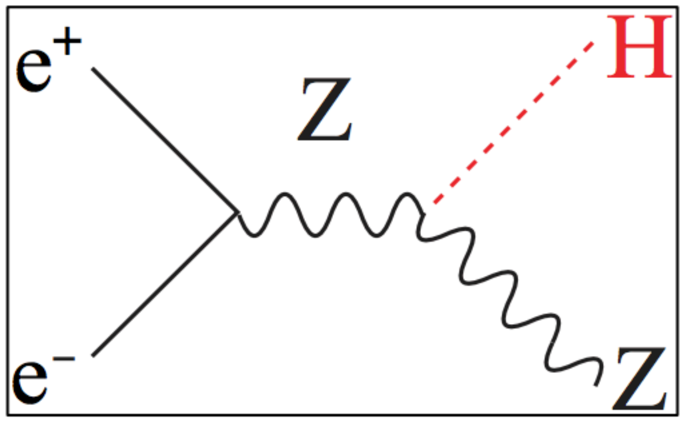
CERN-OPEN-2018-006

Strategic R&D Programme on

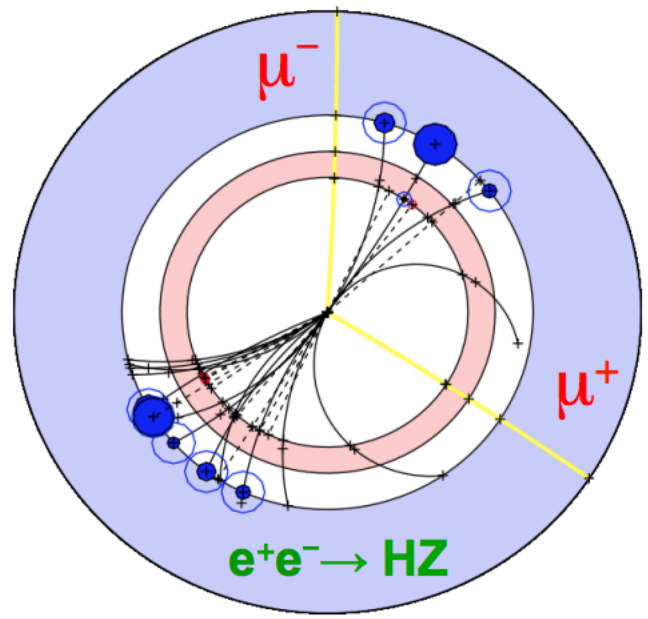
Technologies for Future Experiments

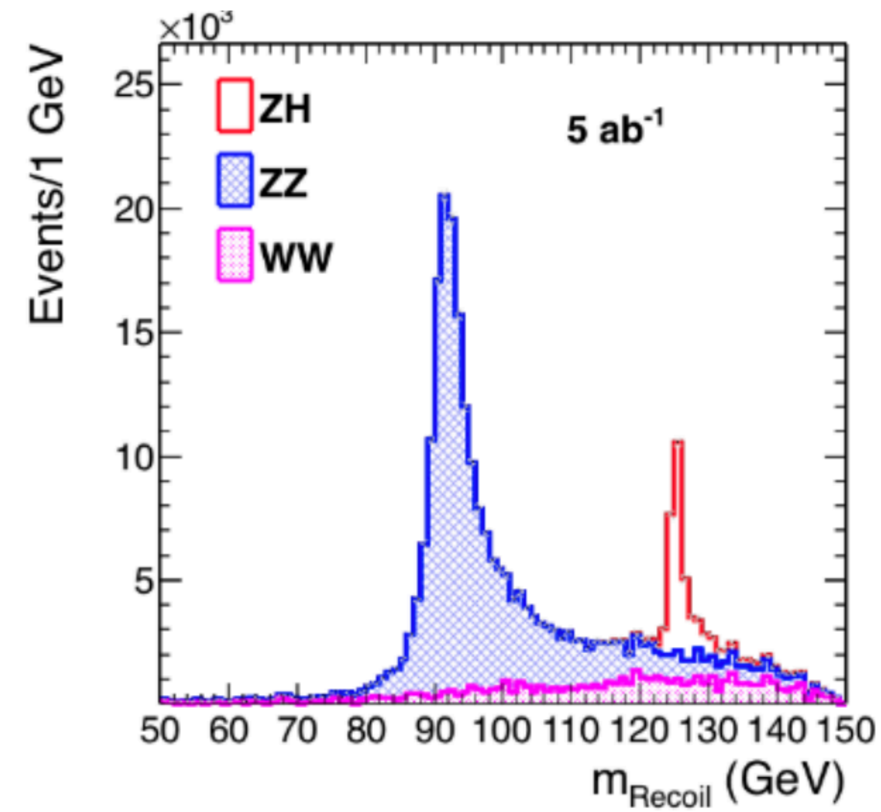
Recap: Higgs @ e+e- colliders

- **Higgs tagged by a Z, Higgs mass from Z recoil**



$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$





Higgs recoil mass measurement → production cross section:

- 10^6 Higgs produced @ FCC-ee
- rate ~ $g_Z{}^2$ → $\delta g_Z/g_Z$ ~ 0.1 %

provides absolute g_Z coupling in e+e-

- Then measure ZH → ZZZ
- rate ~ $g_Z{}^4 / \Gamma_H$ → $\delta\Gamma_H / \Gamma_H$ ~ 1 %

BUT limited statistics:

- for rare decay modes
- HH production

- Then measure ZH → ZXX
- rate ~ $g_Z{}^2 g_X{}^2 / \Gamma_H$ → $\delta g_X/g_X$ ~ 1 %

Coupling measurements at ee vs hh

At pp colliders we can only measure:

$$\sigma_{prod}\, BR(i) = \sigma_{prod}\, \Gamma_i / \Gamma_H$$

→ we do not know the total width.

In order to perform global fits, we have to make **model-dependent assumptions**

Instead, by performing measurements of ratios of BRs at hadron colliders:

$$BR(H \to XX) / BR(H \to ZZ) \approx g_X{}^2 / g_Z{}^2$$

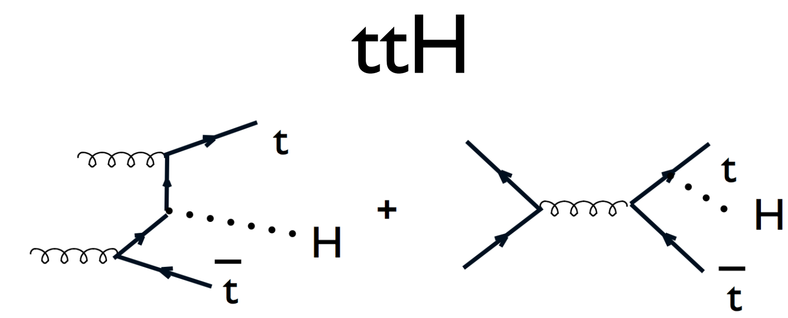
from e^+e^-

We can "convert" **relative measurements into absolute** via g_Z thanks to e^+e^- measurement

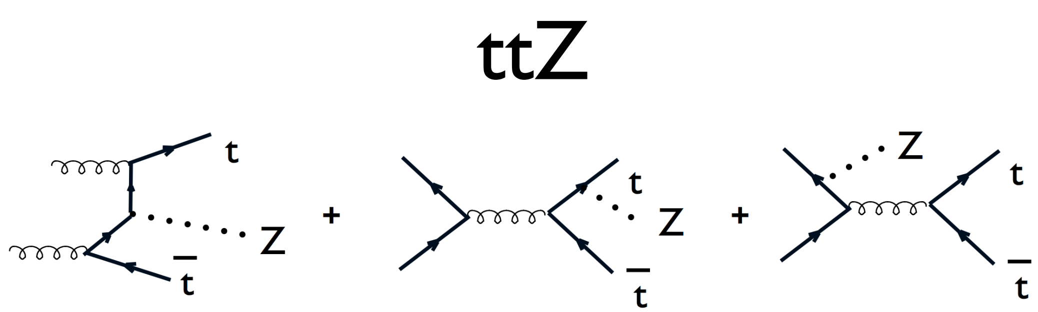
→ synergy between lepton and hadron colliders

MLM, D. Jamin, C. Helsens, G. Ortona, MS

Top Yukawa (production)

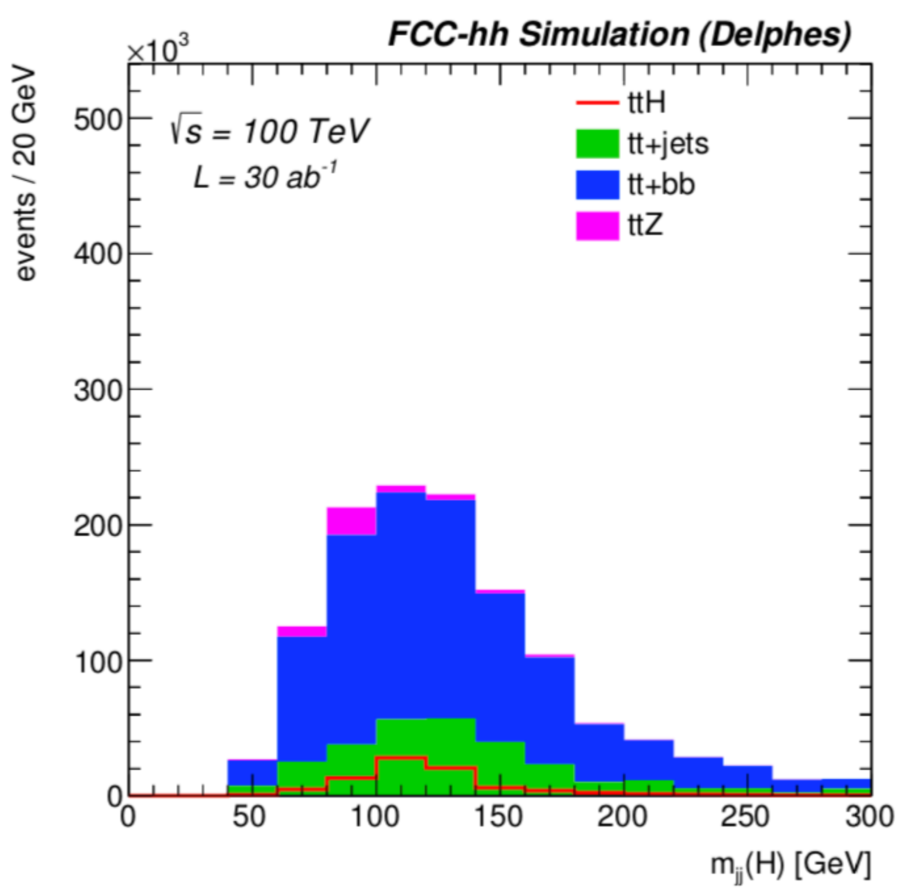


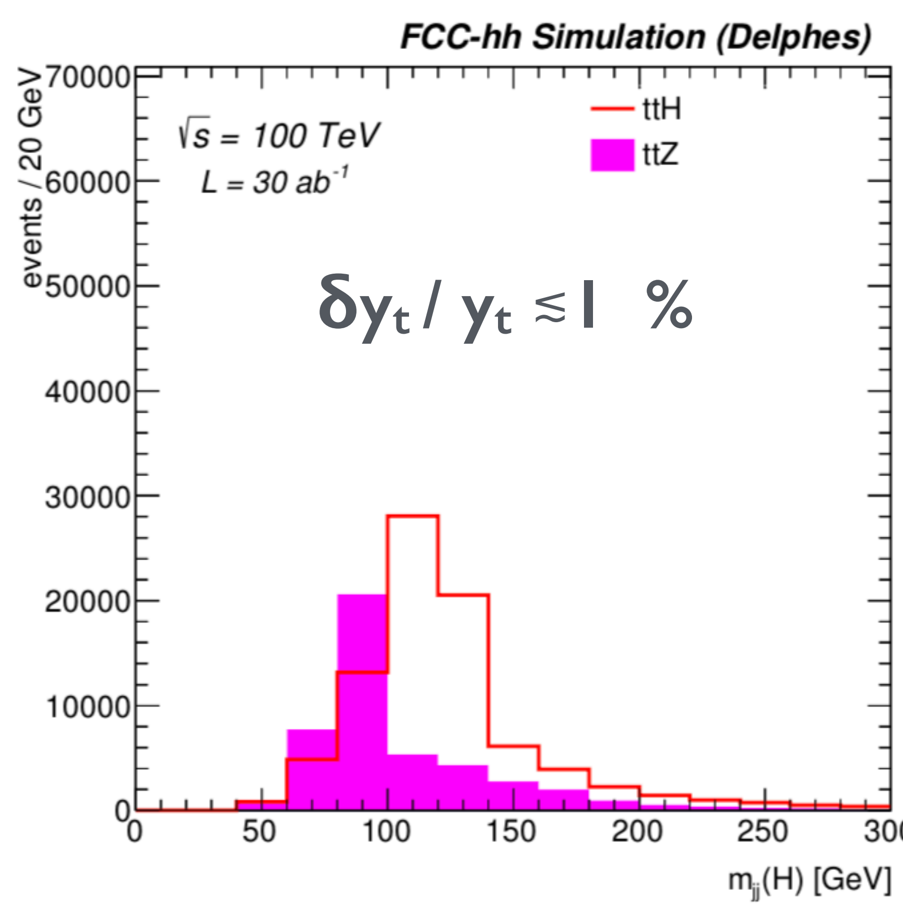
- production ratio **σ(ttH)/σ(ttZ)** ≈ $y_t^2\ y_b^2/\ g_{ttZ}{}^2$
- measure **σ(ttH)/σ(ttZ)** in **H/Z→bb** mode in the boosted regime, in the **semi-leptonic** channel
- perform **simultaneous fit of double Z and H peak**
- (lumi, scales, pdfs, efficiency) **uncertainties cancel out** in ratio



- assuming g_{ttZ} and κ_b known to 1% (from FCC-ee),

  → measure y_t to 1%





Higgs decays: γγ - ZZ - Zγ - μμ

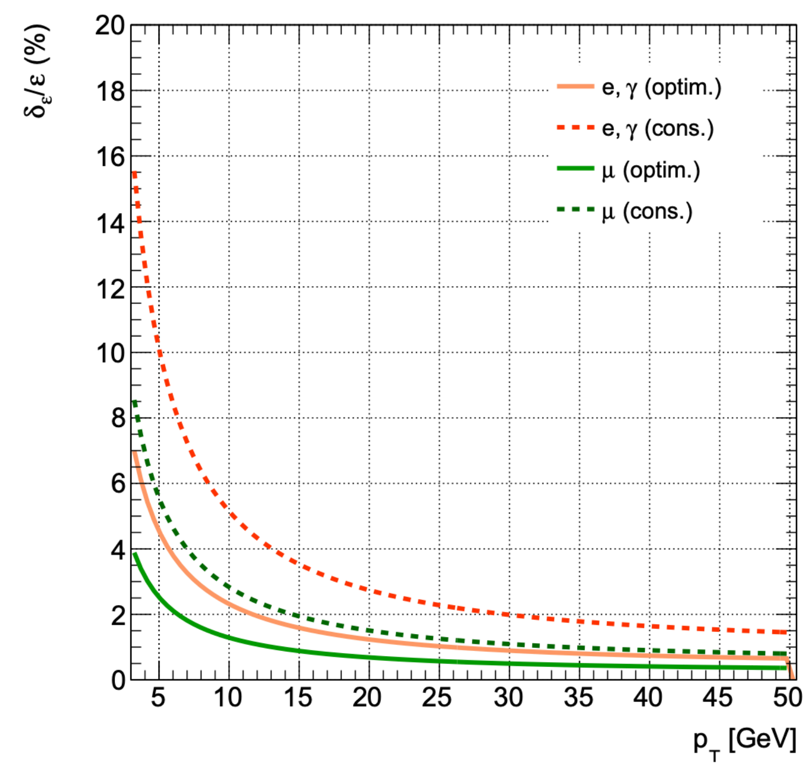
- **1% systematics on (production x luminosity)**, meant as a reference target. Assumes good theoretical progress over the next years, and **reduction of PDF+α_S uncertainties with HL-LHC + FCC-ee**.

- **e/μ/γ efficiency systematics** (shown on the right). In situ calibration, with the immense available statistics in possibly new clean channels ($Z \to \mu\mu\gamma$), will most likely reduce the uncertainties.

- All final states considered here rely on **reconstruction of m_H** to within few GeV.
  - **backgrounds** (physics and instrumental) to be **determined with great precision from sidebands** (~ infinite statistics)

  - **Impact of pile-up**: hard to estimate with today's analyses.
    → **Focus on high-p_T objects** will help to decrease relative impact of pile-up

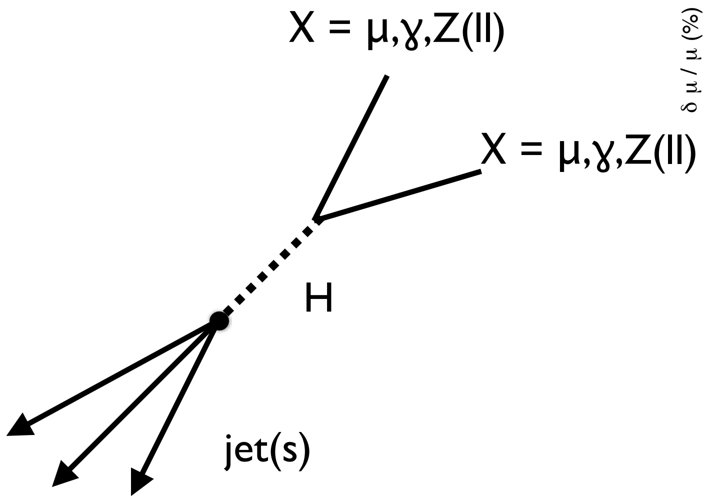
  - Following **scenarios** are considered:
    - δ_{stat} → stat. only (I) (signal + bkg)
    - δ_{stat} , δ_{eff} → stat. + syst. (II)
    - δ_{stat} , δ_{eff} , δ_{prod} = 1% → stat. + syst. + prod (III)

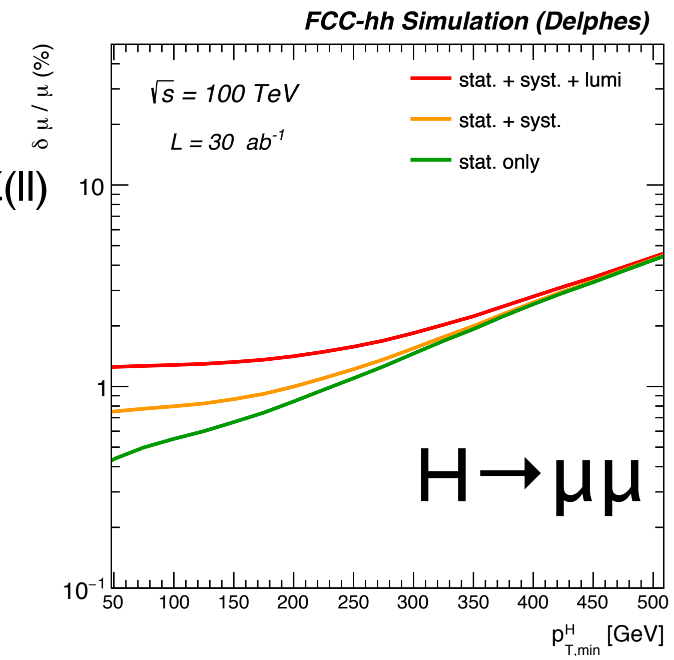


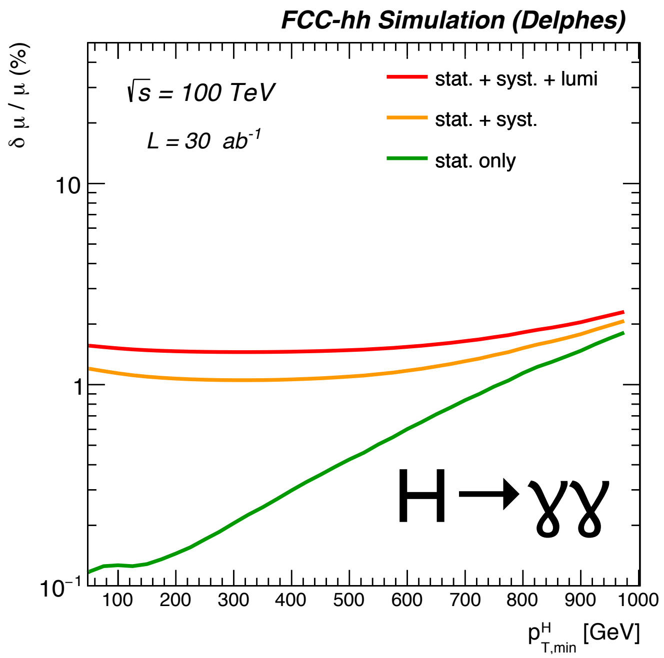
Higgs decays (signal strenth)

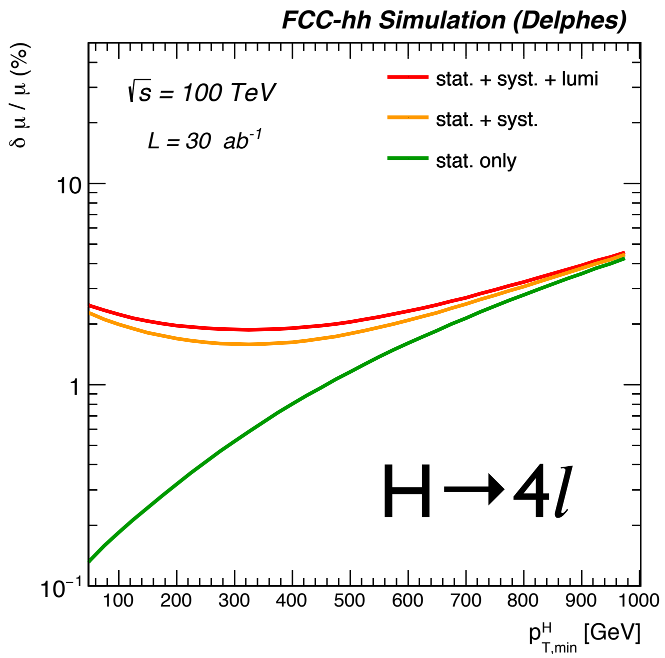
- 1% lumi + theory uncertainty
- p_T dependent object efficiency:
  - $\delta\varepsilon(e/\gamma)$ = 0.5 (1)% at $p_T \to \infty$
  - $\delta\varepsilon(\mu)$ = 0.25 (0.5)% at $p_T \to \infty$

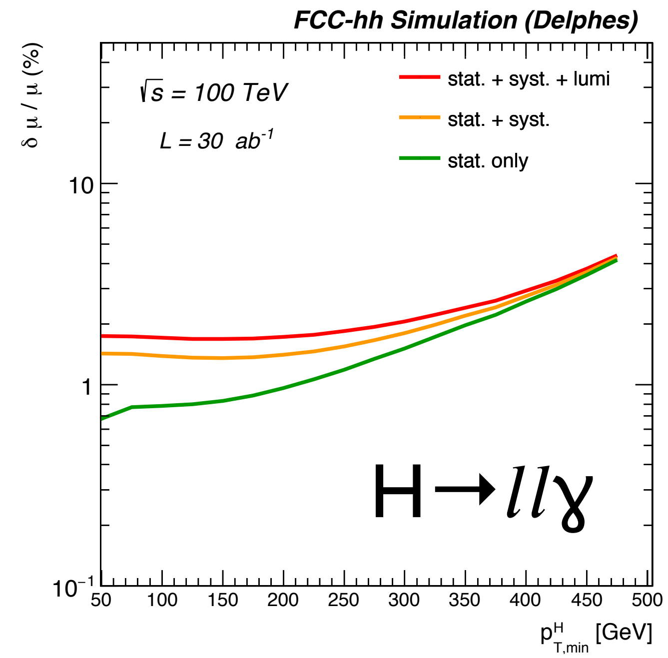
- study sensitivity as a function of **minimum p_T(H)** requirement in the **$\gamma\gamma$, ZZ(4l), $\mu\mu$ and Z(ll)γ** channels
- **low** p_T(H): **large statistics** and **high syst**. unc.
- **large** p_T(H): **small statistics** and **small syst**. unc.
- **O(1-2%) precision on BR** achievable up to very high p_T (means 0.5-1% on the couplings)



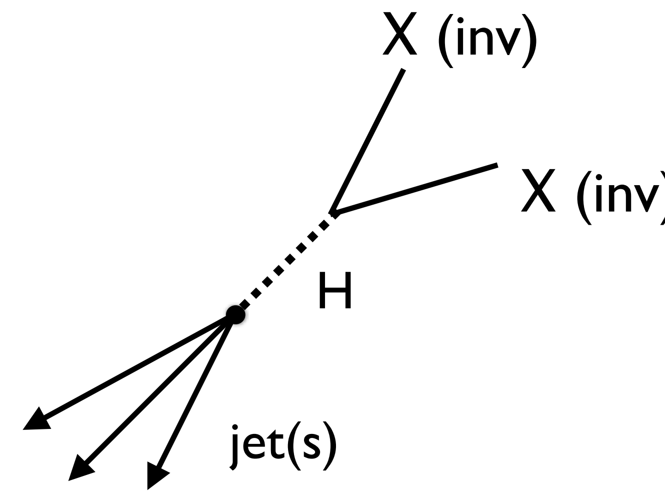






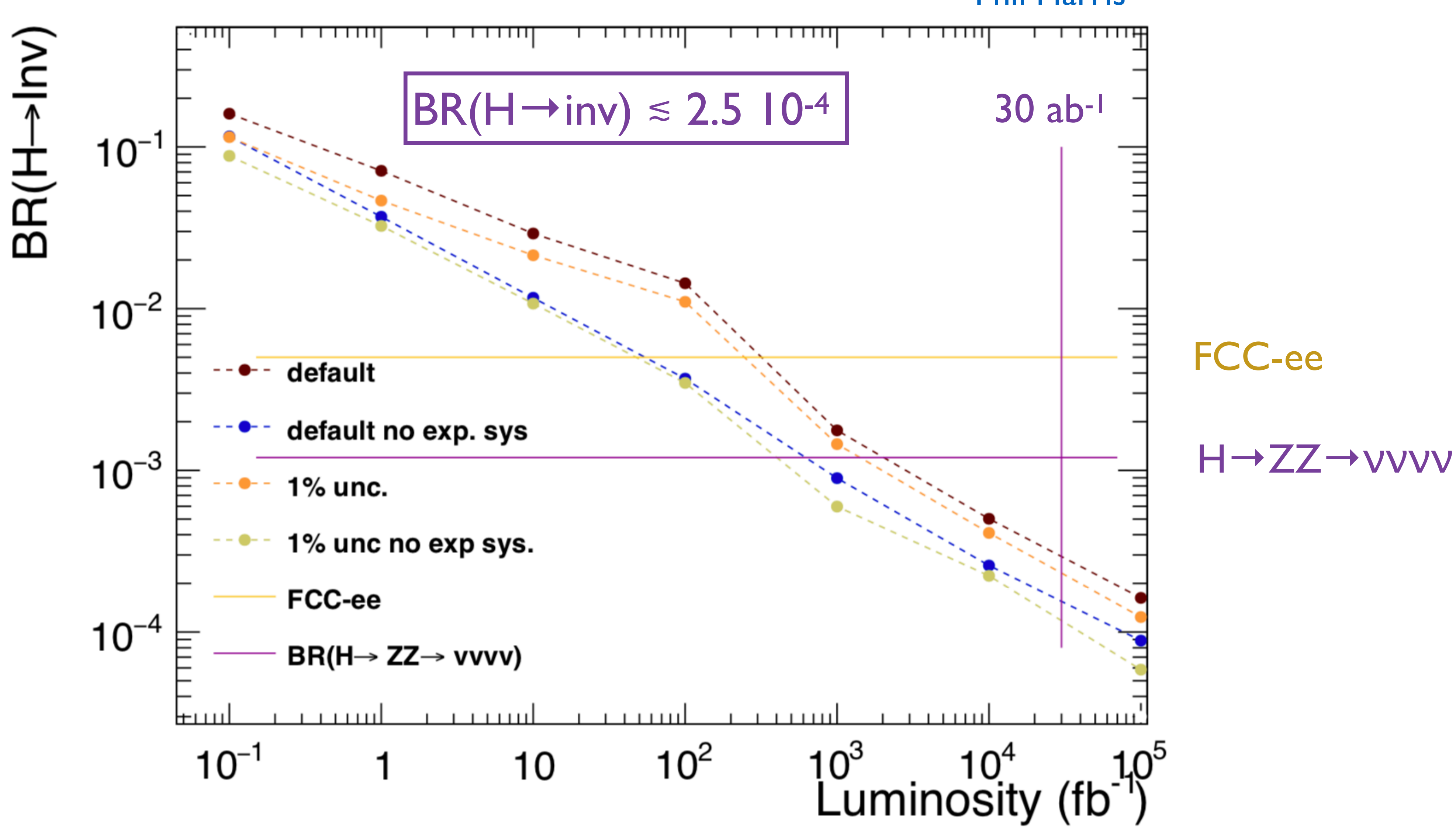


H→invisible



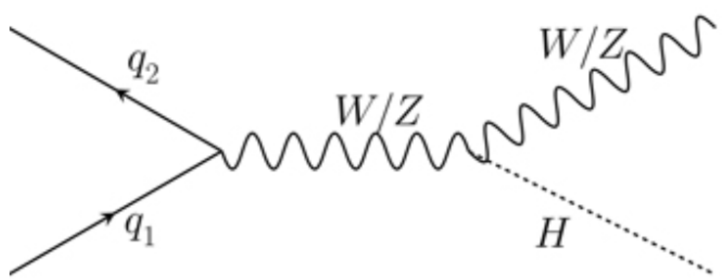
- Measure it from H + X at **large p_T(H)**
- Fit the **E_T^{miss}** spectrum
- Constrain background p_T spectrum from **Z→νν** to the % level using NNLO QCD/EW to relate to measured Z,W and γ spectra (low stat)
- Estimate Z→νν (W→lν) from Z→ee/μμ (W→lν) control regions (high stat).

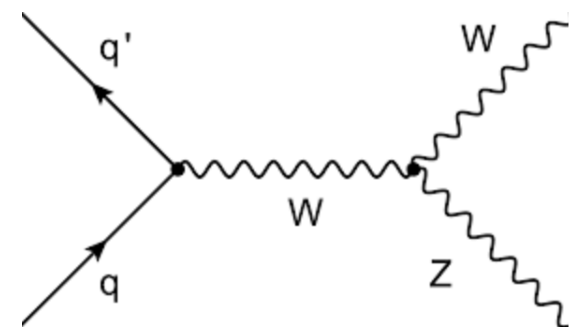
Phil Harris



Standalone 100 TeV Higgs measurements

- Following the principle of **reducing** as much as possible **the impact of systematics** assumptions on future measurements, additional **ratio measurements**:





$\sigma(WH[\to\gamma\gamma]) / \sigma(WZ[\to e^+e^-]) \longrightarrow G_W = g^2_{HWW} \times BR(H \to \gamma\gamma)$

$\sigma(WH[\to\tau\tau]) / \sigma(WZ[\to\tau\tau]) \longrightarrow G_\tau = g^2_{HWW} \times BR(H \to \tau\tau)$

$\sigma(WH[\to bb]) / \sigma(WZ[\to bb]) \longrightarrow G_b = g^2_{HWW} \times BR(H \to bb)$

parton level study

p_T^{min} (GeV)	W[e]Z[e] (pb)	W[e]H (pb)	W[ℓ]Z[e] $\times$ L	W[ℓ]H[$\gamma\gamma$] $\times$ L	$\delta R/R$
100	2.1E-2	1.0E-1	1.3E6	1.4E4	8.5E−3
150	1.0E-2	6.3E-2	6.0E5	8.7E3	1.1E−2
200	5.6E-3	3.8E-2	3.4E5	5.2E3	1.4E−2
300	2.1E-3	1.6E-2	1.3E5	2.2E3	2.1E−2

p_T^{min} (GeV)	W[e]Z[τ] (pb)	W[e]H (pb)	W[ℓ]Z[τ] $\times\epsilon_\tau$ L	W[ℓ]H[$\tau\tau$] $\times\epsilon_\tau$ L	$\delta R/R$
100	2.1E-2	1.0E-1	1.3E5	3.8E4	5.9E−3
150	1.0E-2	6.3E-2	6.0E4	2.4E4	7.7E−3
200	5.6E-3	3.8E-2	3.4E4	1.4E4	1.0E−2
300	2.1E-3	1.6E-2			
400	9.8E-4	7.9E-3			

$\delta G/G < 1\%$

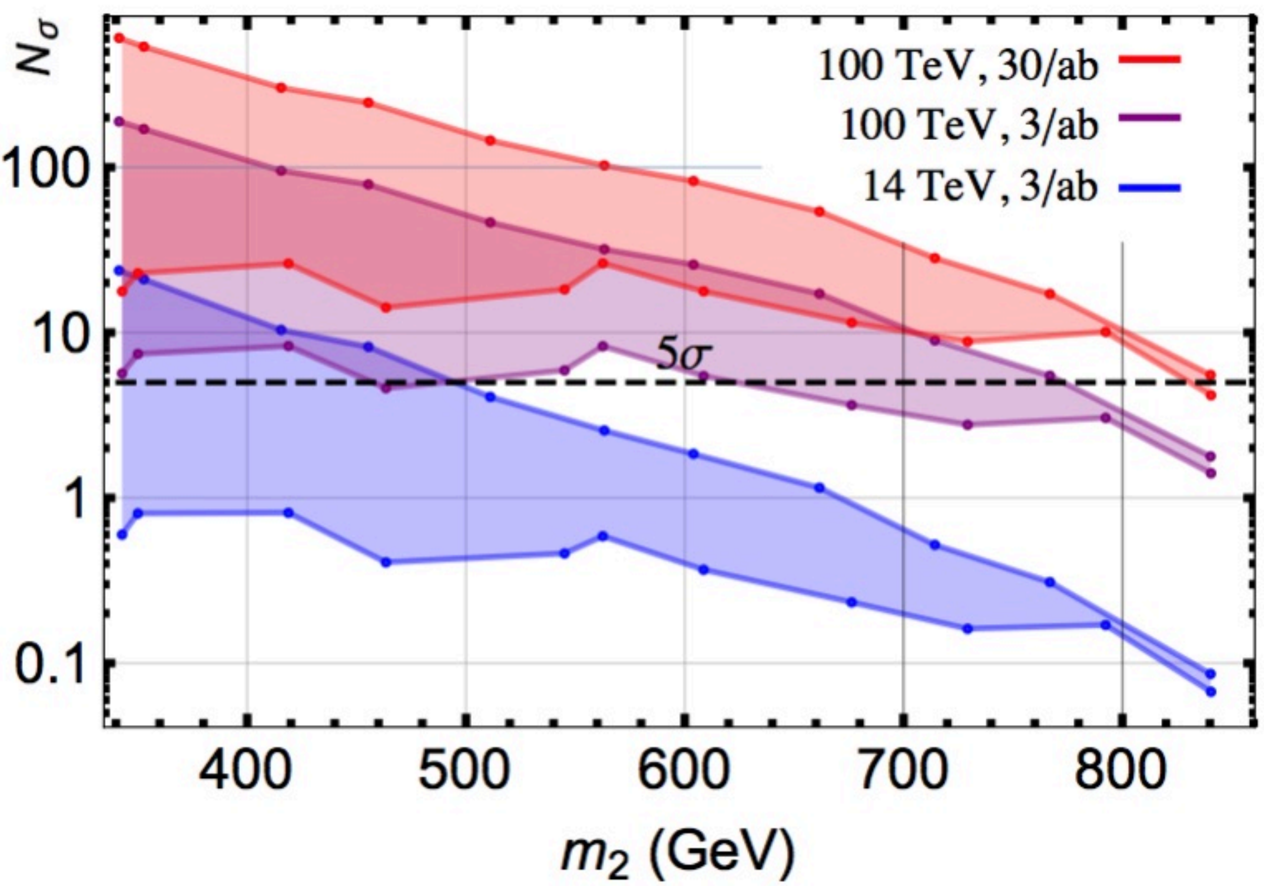
p_T^{min} (GeV)	W[e]+bb (pb) $m[bb] \in m_Z$	W[e]Z[bb] (pb)	W[e]+bb (pb) $m[bb] \in m_H$	W[e]H (pb)	W[ℓ] bb $\times\epsilon_b$ L $m[bb] \in m_Z$	W[ℓ]Z[bb] $\times\epsilon_b$ L	W[ℓ] bb $\times\epsilon_b$ L $m[bb] \in m_H$	W[ℓ]H[bb] $\times\epsilon_b$ L	$\delta R/R$
200	3.3E−2	2.5E−2	2.3E−2	3.8E−2	9.9E5	7.5E4	6.9E5	6.6E5	2.5E−3
300	1.2E−2	9.2E−3	8.8E−3	1.6E−2	3.6E5	5.5E4	2.6E5	2.8E5	3.2E−3
400	5.5E−3	4.3E−3	4.1E−3	7.9E−3	1.7E5	2.6E5	1.2E5	1.4E5	4.5E−3
600	1.7E−3	1.4E−3	1.3E−3	2.6E−3	5.1E4	8.4E4	3.9E4	4.5E4	7.8E−3
800	6.8E−4	6.2E−4	5.0E−4	1.2E−3	2.0E4	3.7E4	1.5E4	2.1E4	1.1E−2

also: $\sigma(Z[\nu\nu]H[\to\gamma\gamma]) / \sigma(Z[\nu\nu]Z[\to e^+e^-])$

Higgs Self-coupling and constraints on models with 1st order EWPT

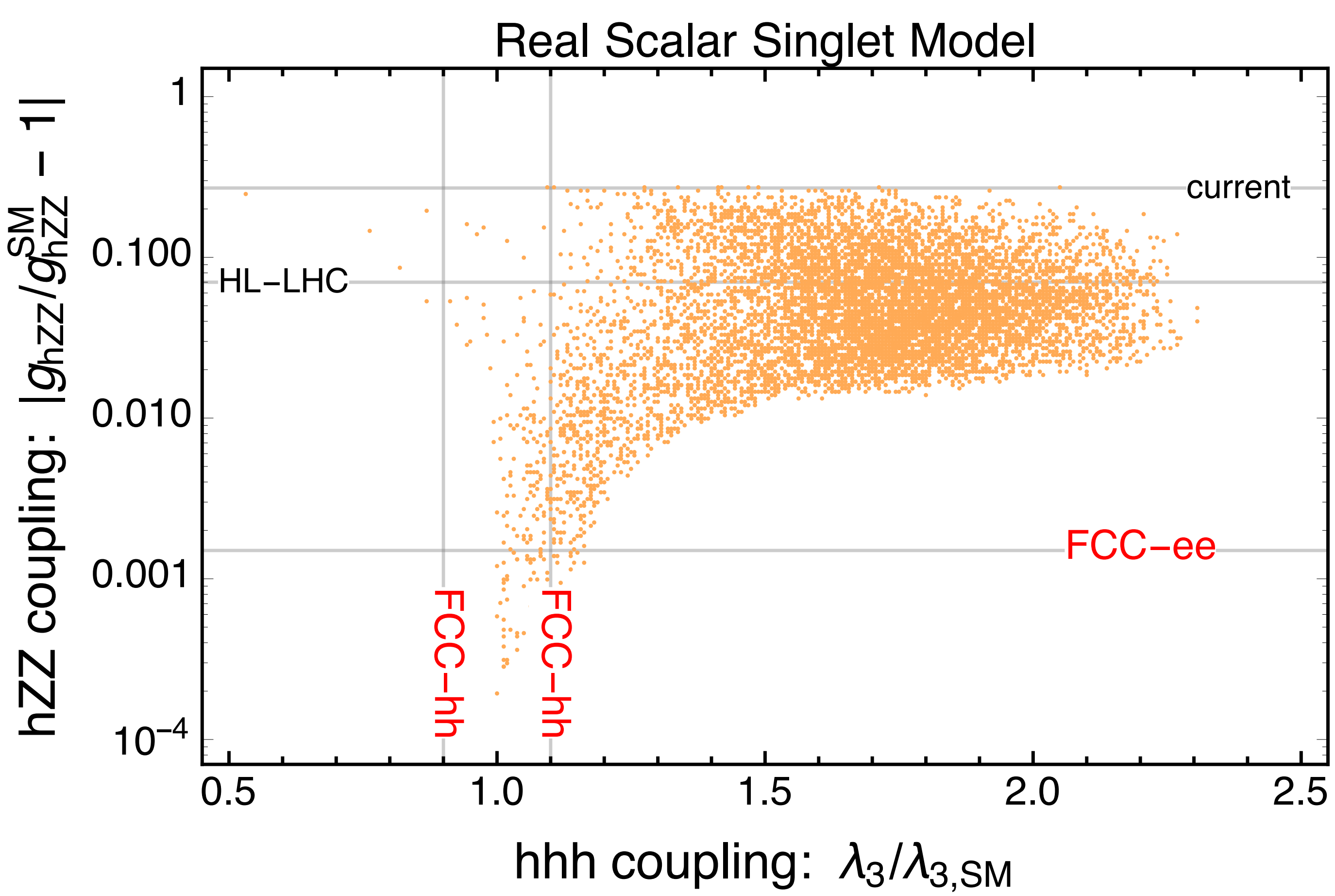
- **Strong 1st order electroweak phase transition** (and CP violation) needed to explain large observed **baryon asymmetry** in our universe
- Can be achieved with extension of SM + singlet

Direct detection of extra Higgs states



$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$

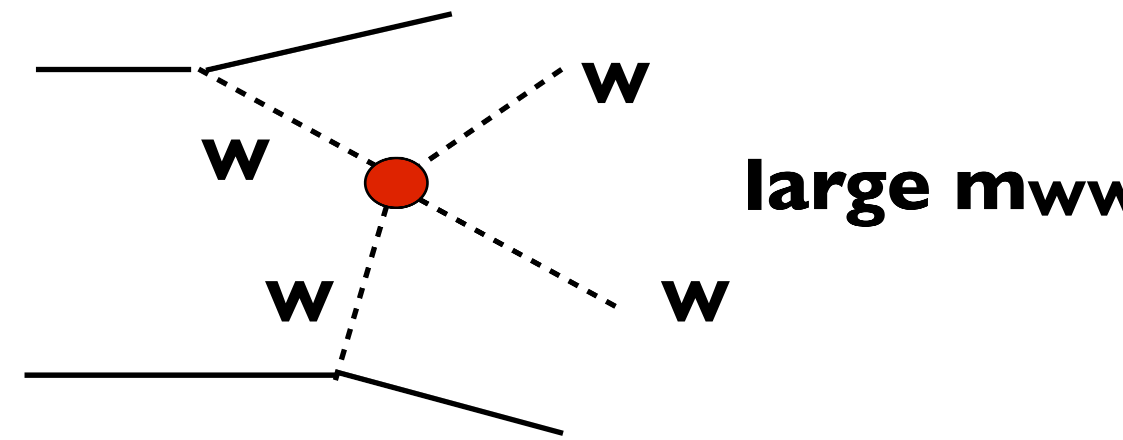
Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



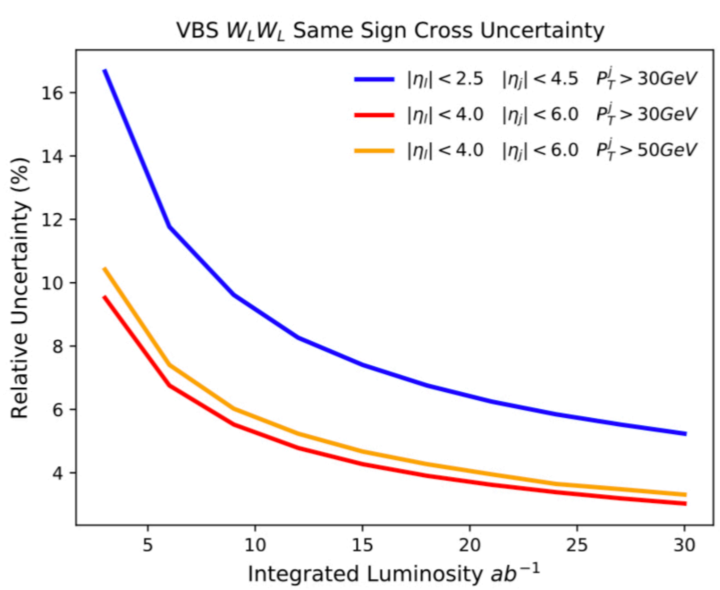
Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

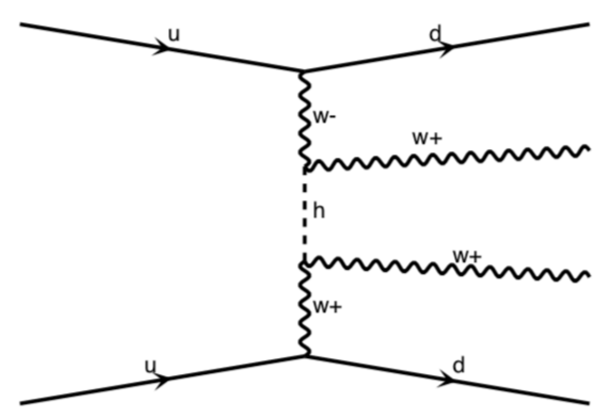
Vector Boson Scattering

A. Sznajder, MS



- Sets constraints on **detector acceptance** (fwd jets at **η≈4**)
- Study **W+/-W+/- (same-sign)** channel
- **Large WZ** background at FCC-hh
- **3-4% precision on W_LW_L scattering** xsec. achievable with full dataset (only 3σ HL-LHC)
- Indirect measurement of HWW coupling possible, **$\delta\kappa_W/\kappa_W \approx 2\%$**





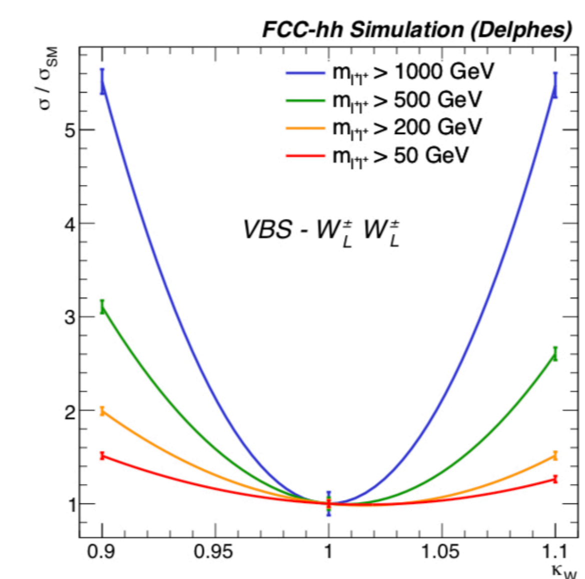
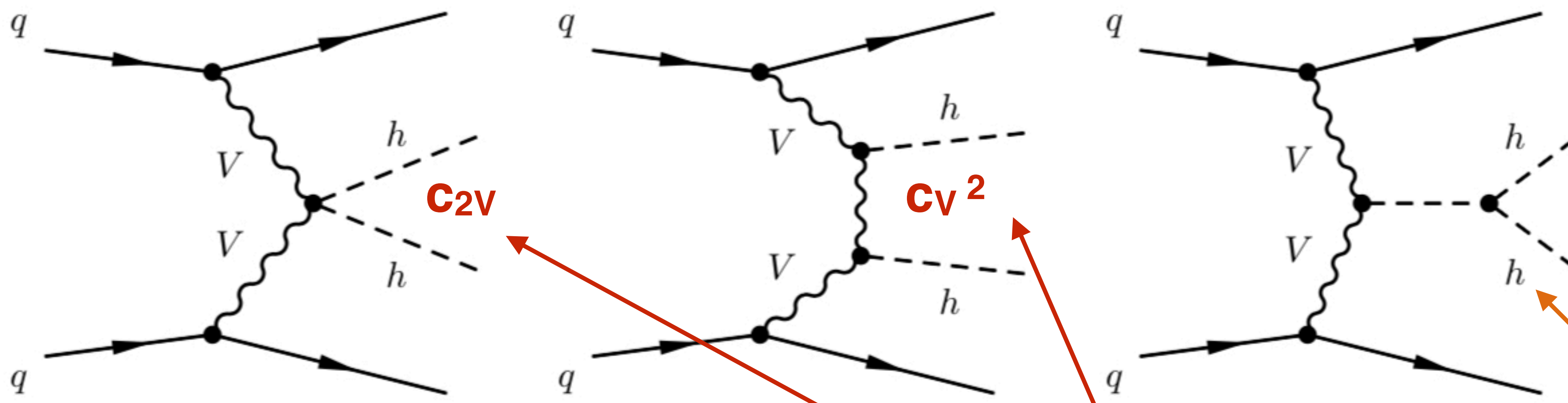


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_LW_L \to HH$ process.

$m_{l^+l^+}$ cut	$>$ 50 GeV	$>$ 200 GeV	$>$ 500 GeV	$>$ 1000 GeV
$\kappa_W \in$	[0.98,1.05]	[0.99,1.04]	[0.99,1.03]	[0.98,1.02]

$W_L W_L \to HH$

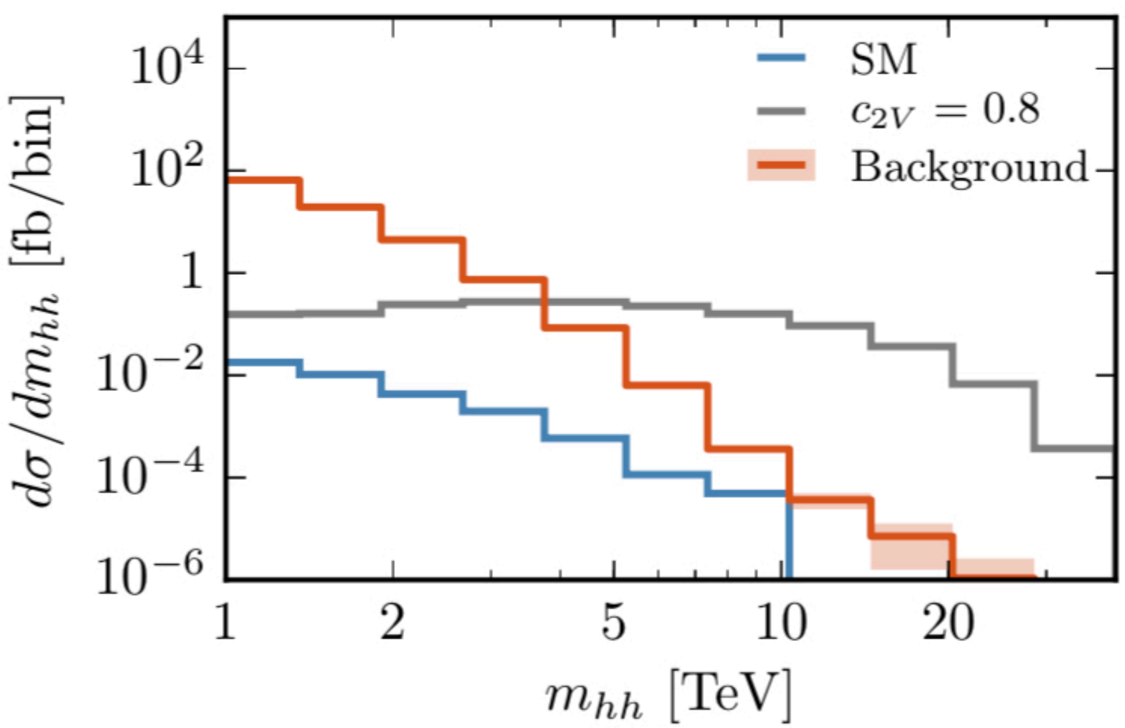
F. Bishara, R. Contino, J. Rojo

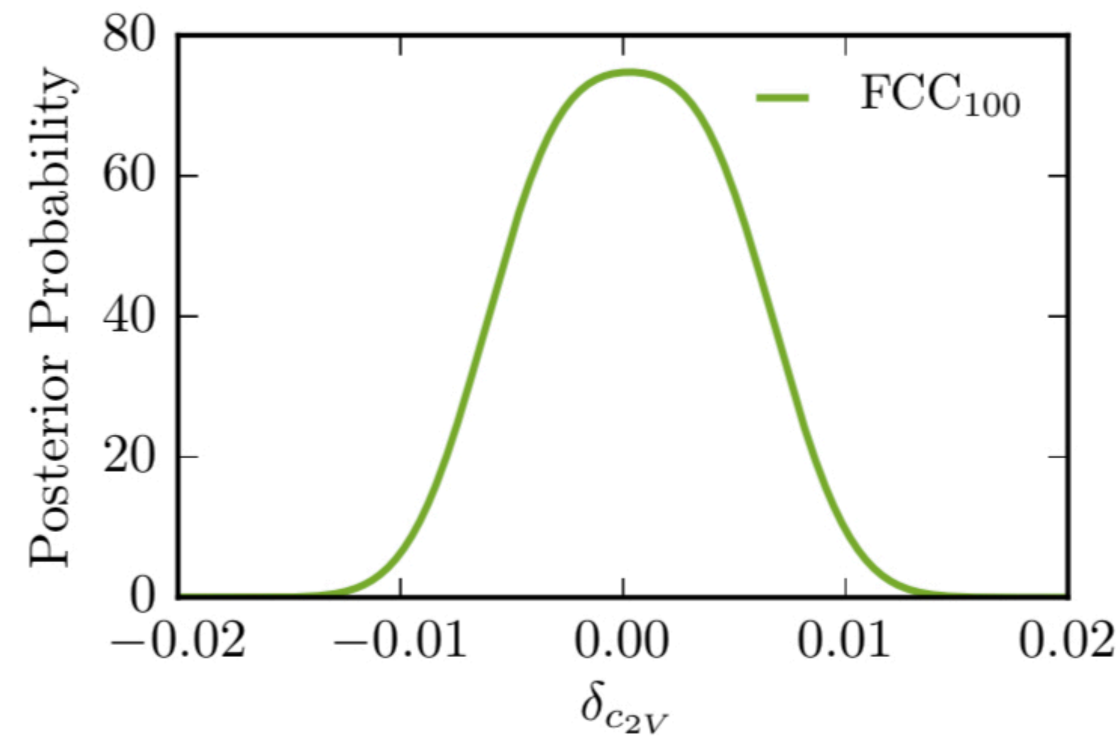


negligible at large m_{HH}

$$A(V_L V_L \to HH) \sim \frac{\hat{s}}{v^2}\underbrace{(c_{2V} - c_V^2)}_{\text{0 in the SM}} + \mathcal{O}(m_W^2/\hat{s}),$$

high energy behaviour driven by C_{2V} and C_V, if $\delta C_{2V} \neq 0$, grows with E





With c_V from FCC-ee, $\delta c_{2V} < 1\%$

Towards defining the FCChh detector

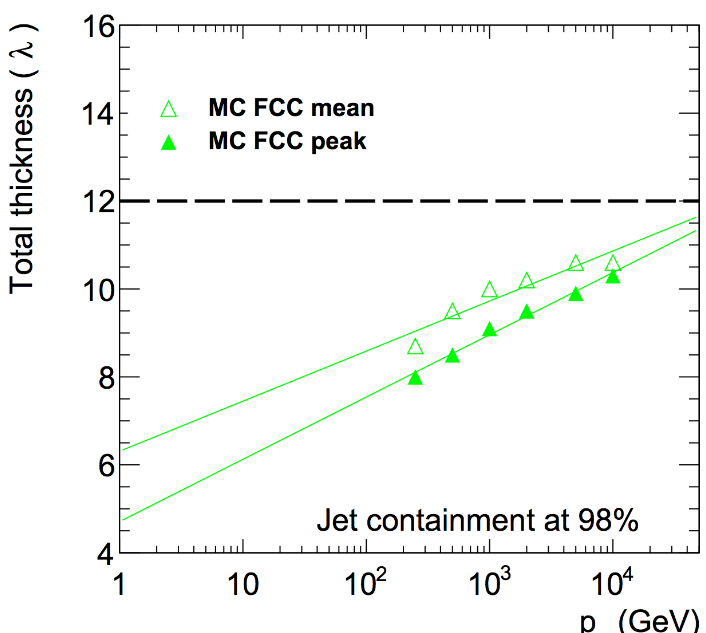
Physics constraints

- The boosted regime:
  → measure leptons, jets, photons, muons originating multi-TeV resonances

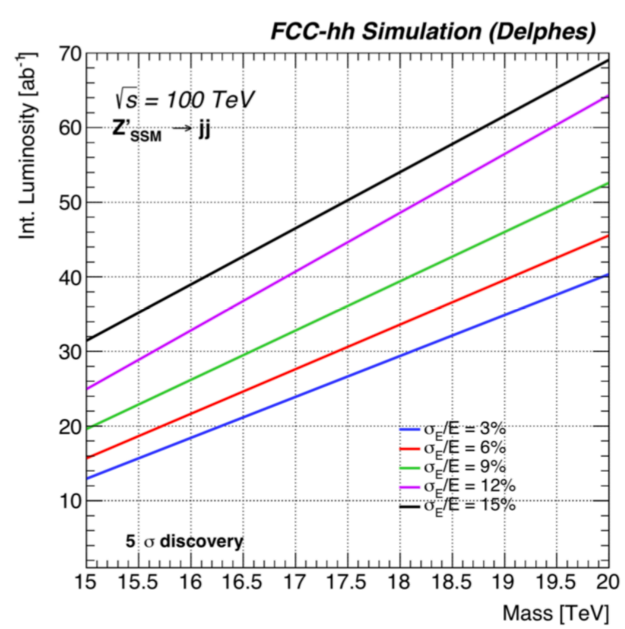
Tracking: $\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$

Calorimeters: $\frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} \bigoplus B$

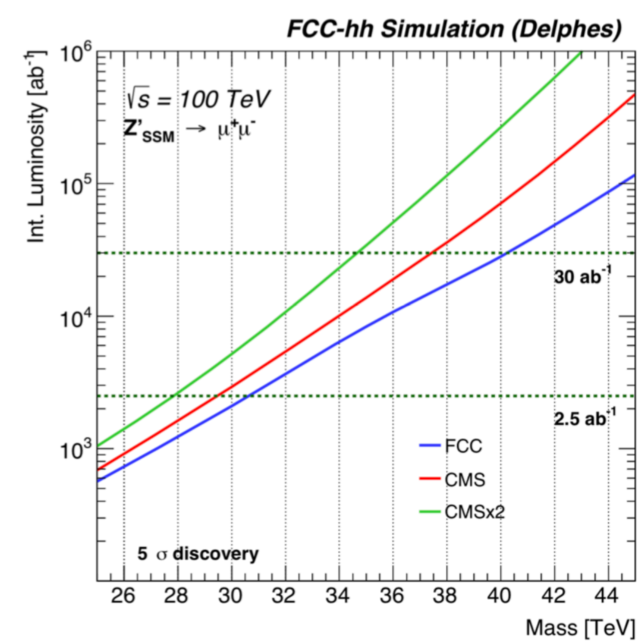
- Tracking target : **σ / p = 20% @10 TeV**
- Muons target: **σ / p = 10% @20 TeV**
- Calorimeters target: containment of p_T = 20 TeV jets



≳11 λ_I for EM + Had



high p_T jets



high p_T muons

Towards defining the FCChh detector

Physics constraints

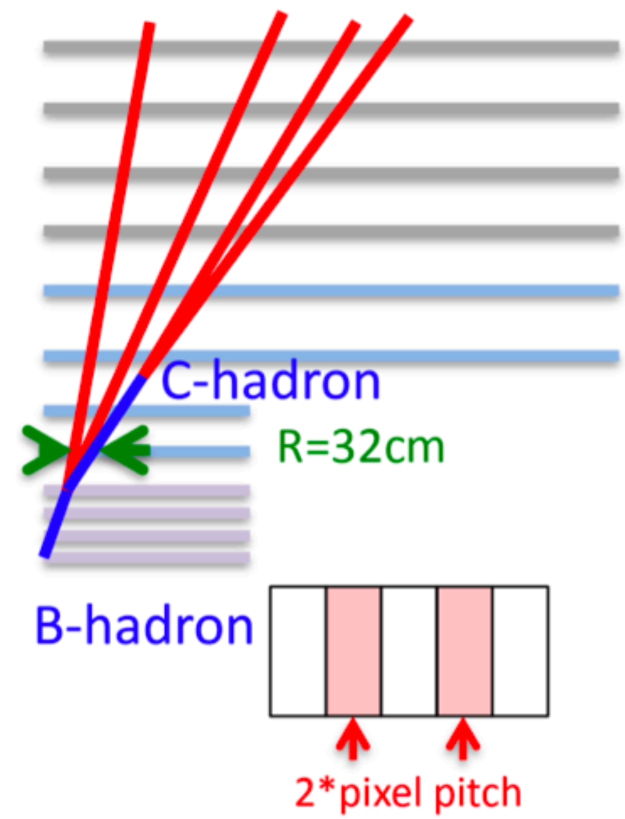
- The boosted regime:
  → measure b-jets, taus from multi-TeV resonances

- Long-lived particles live **longer**:

ex: 5 TeV **b-Hadron** travels **50 cm** before decaying
5 TeV **tau lepton** travels **10 cm** before decaying

→ extend pixel detector further?
- useful also for exotic topologies (disappearing tracks and generic BSM Long-lived charged particles)
- number of channels over large area can get too high

→ re-think reconstruction algorithms:
- hard to reconstruct displaced vertices
- **exploit hit multiplicity discontinuity**



Only 71% 5 TeV b-hadrons decay < 5th layer.

- displaced vertices

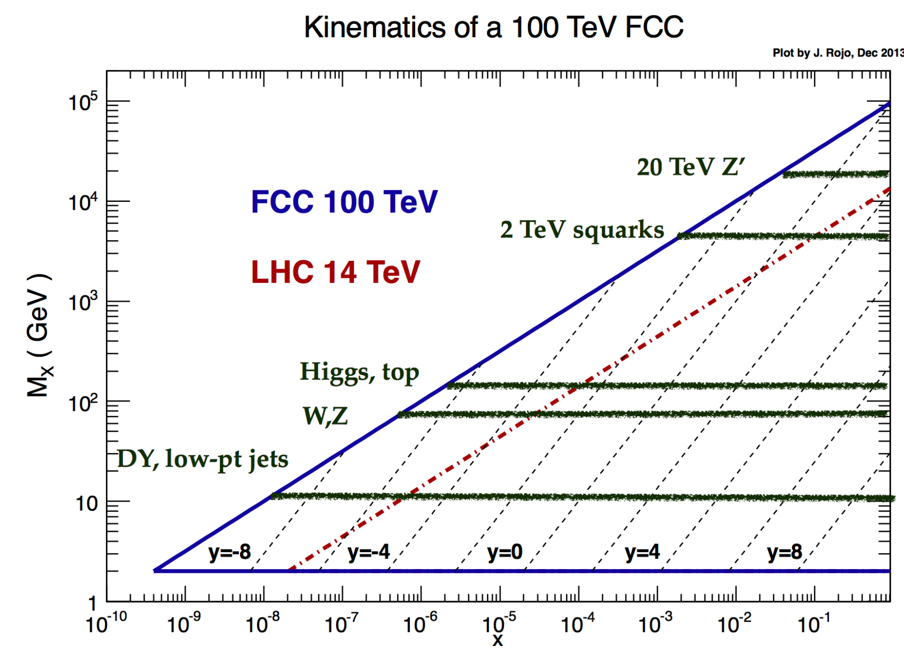
SM physics @ 100 TeV

$$x_1 * x_2 * s = M^2$$

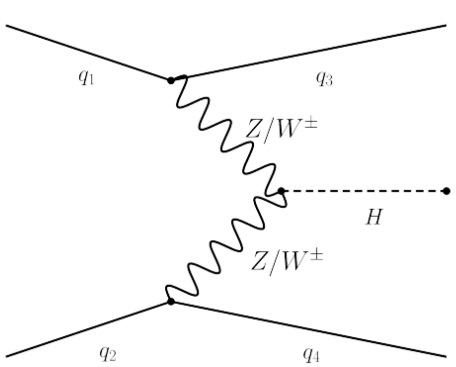
SM Physics is more forward @100TeV

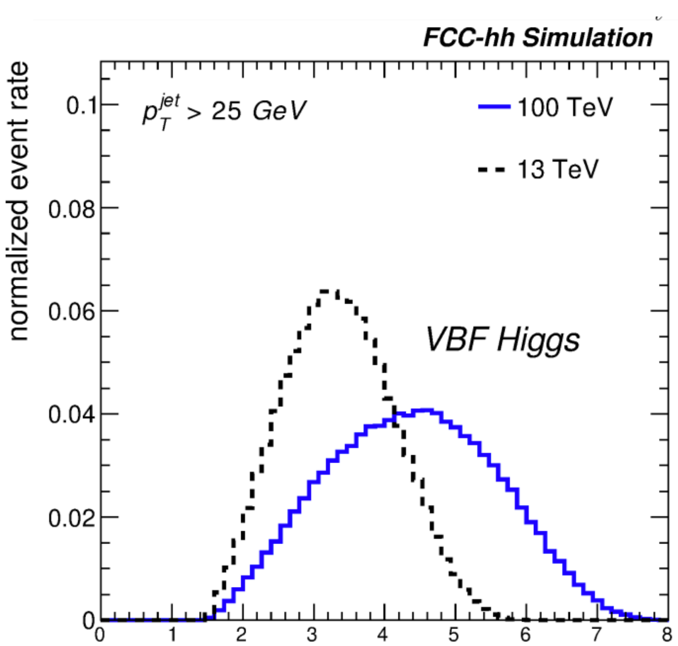
- in order to maintain sensitivity in need **large rapidity** (with tracking) and **low p_T** coverage

→ highly challenging levels of radiation at large rapidities

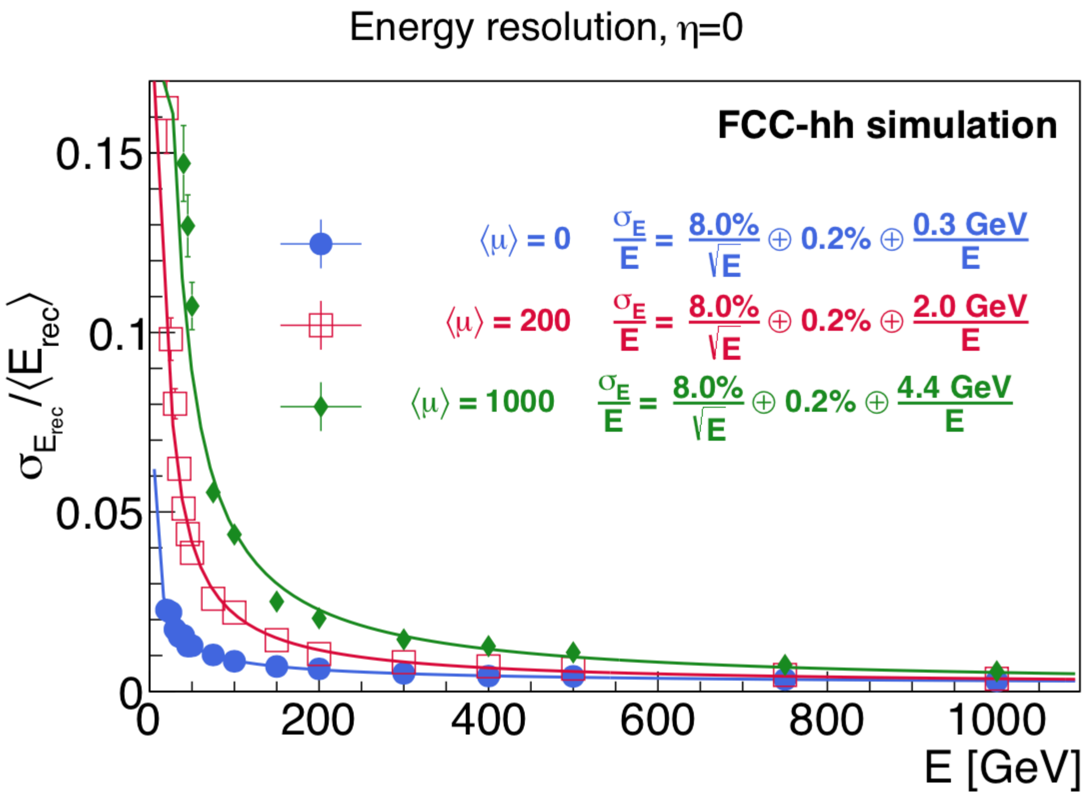


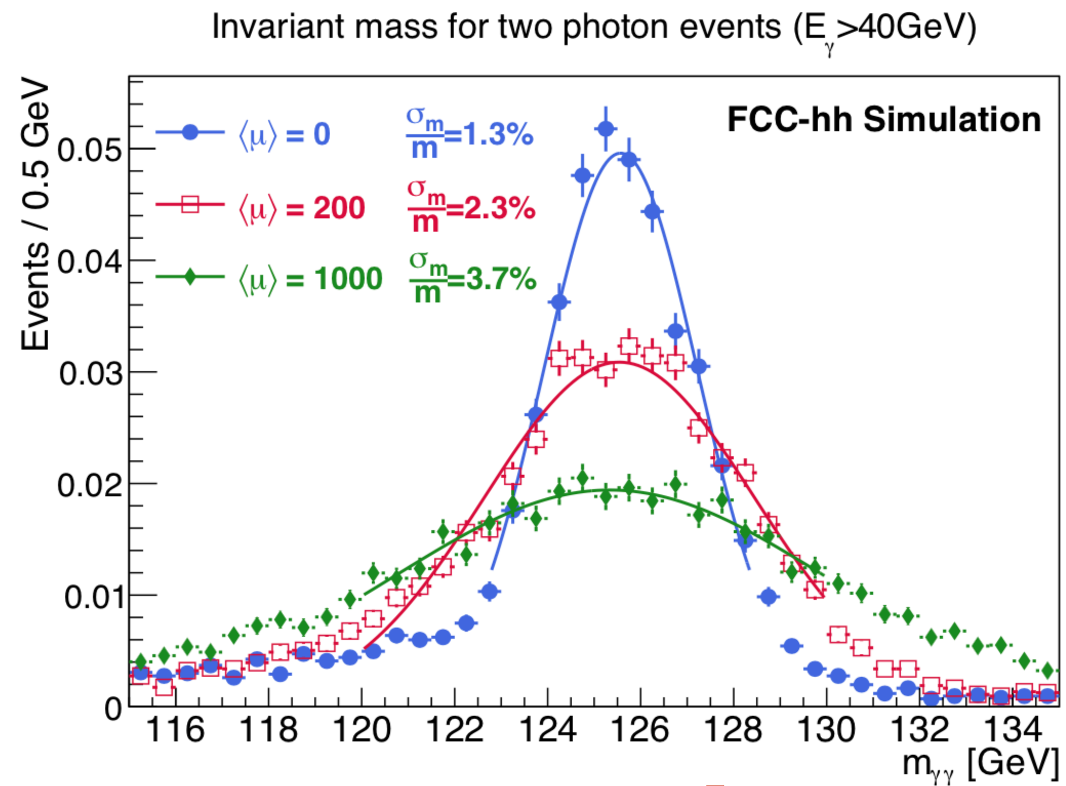
- Goals:
  - **Precision spectroscopy** and calorimetry up to **|η| < 4**
  - Tracking and calorimetry up to |η| < 6





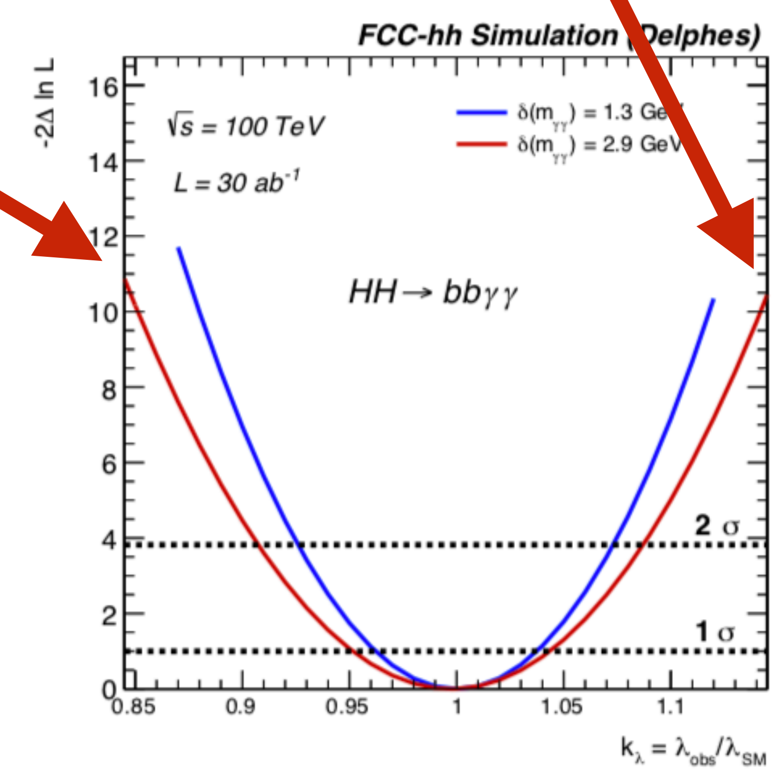
Photon resolution with PU





Large impact of in time PU on the noise term (out of the box with no improvements)!!

- severely degrades $m_{\gamma\gamma}$ resolution (improving clustering, not sliding windows may help)
- impacts Higgs self-coupling precision by $\delta\kappa_\lambda \approx 1\%$
- some thought needed (tracking, timing information can help?)

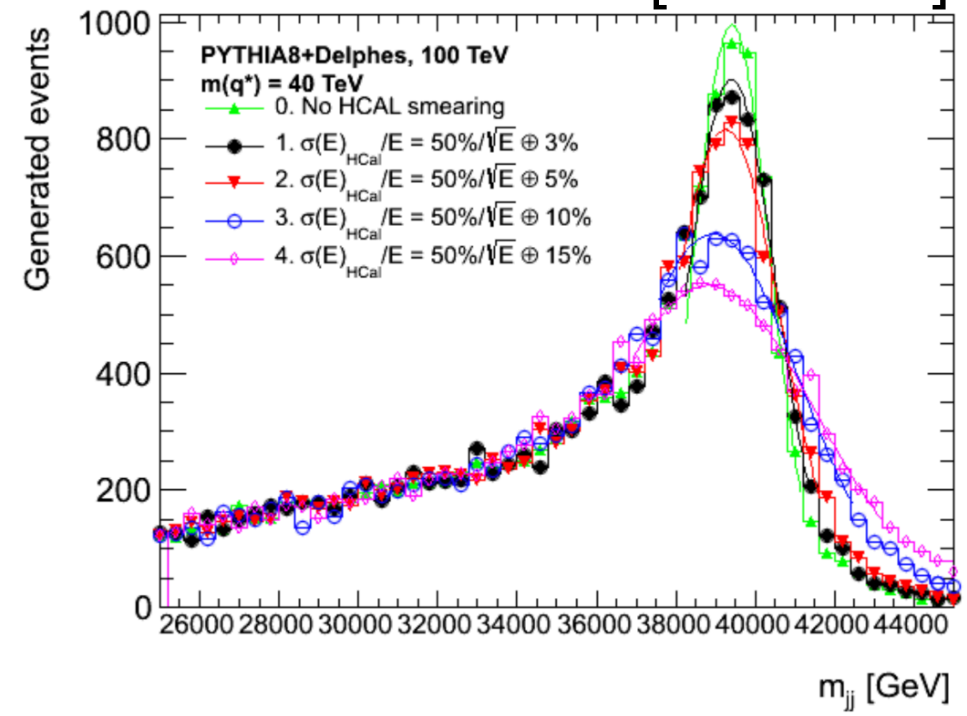


m(γγ) resolution

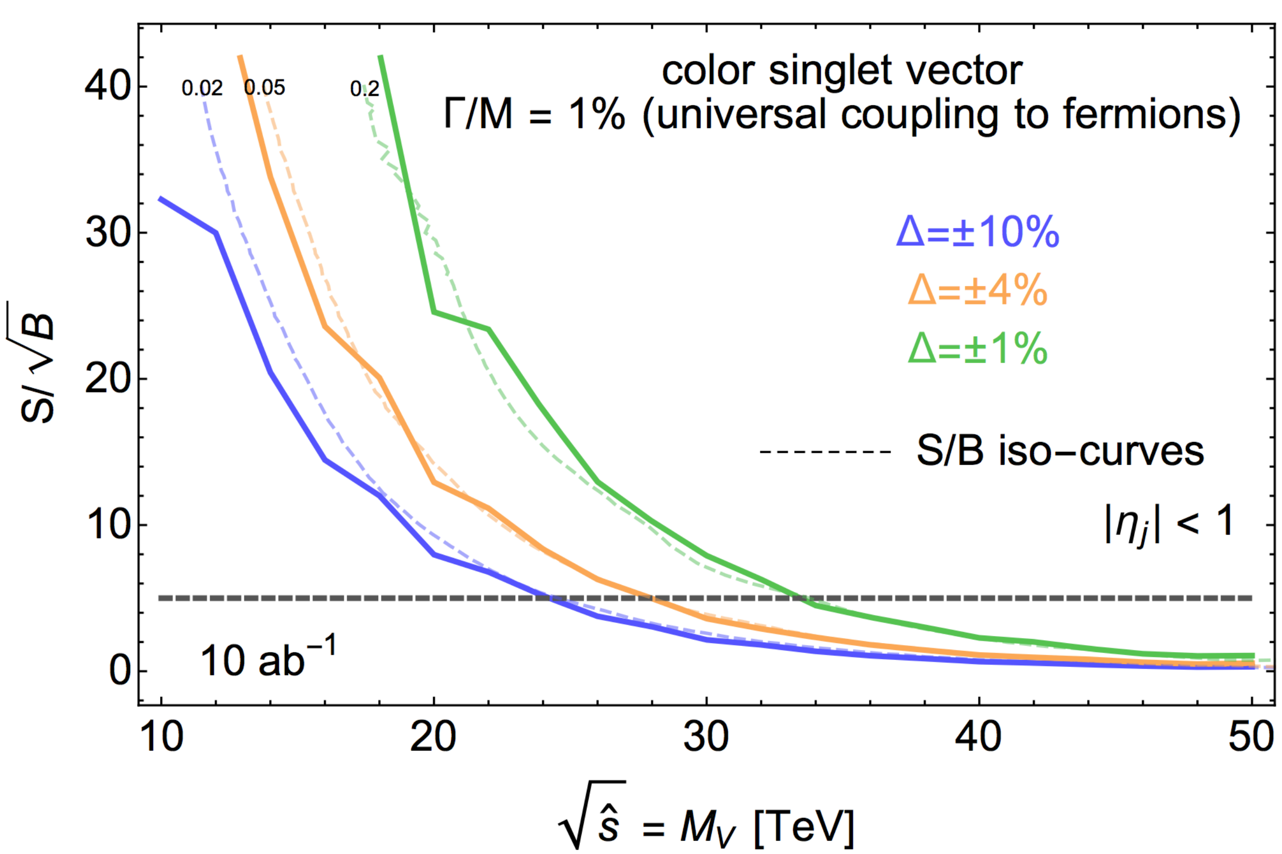
High Mass resonances

- Constant term drives jet energy resolution at high p_T
- Directly impacts sensitivity for excluding discovering narrow resonance high mass resonances $Z' \to j\,j$
- Small impact on strongly coupled (wide) resonances

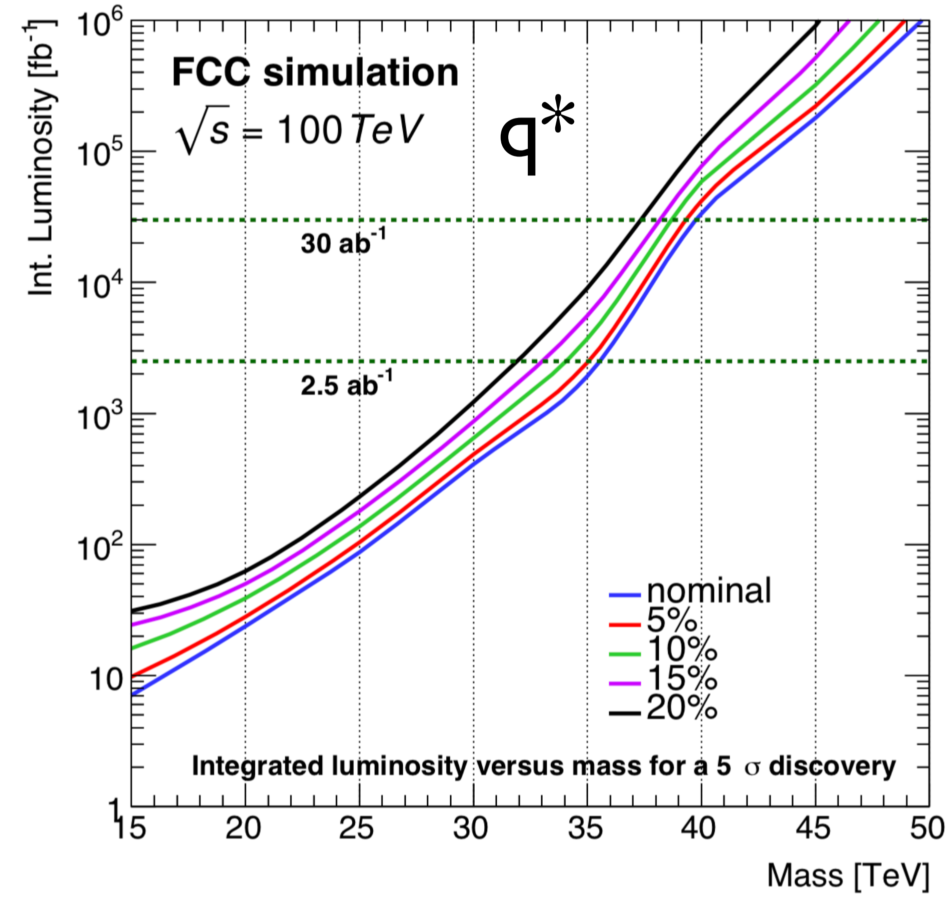
[1606.00947]



Narrow resonances



Wide resonances



Precision vs. sensitivity

- We often talk about "**precise**" SM measurements. What we actually aim at is "**sensitive**" tests of the Standard Model, where *sensitive* refers to the ability to reveal BSM behaviours.
- **Sensitivity** may not require extreme precision. Going after "sensitivity", rather than *just* precision, opens itself new opportunities .
- For example, in the context of dim. 6 operators in EFT, some operators grow with energy:

BR measurement: $\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$ $\Rightarrow$ **precision** probes large Λ

e.g. δO=1% $\Rightarrow$ Λ ~ 2.5 TeV

$\sigma(p_T > X)$: $\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$ $\Rightarrow$ **kinematic reach** probes large Λ

e.g. δO=15% at Q=1 TeV $\Rightarrow$ Λ~2.5 TeV